International Journal of Advances in Engineering and Management (IJAEM)
Volume 4, Issue 8 Aug. 2022, pp: 280-286 www.ijaem.net ISSN: 2395-5252

A Reconfigurable Patch Antenna Review for High Frequency Broadband Applications andCompatible On-Chip Switch Design Performance

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Submitted: 01-08-2022 Revised: 07-08-2022 Accepted: 10-08-2022

ABSTRACT:
Microstrip patch antennas have been a premier choice in RF front end applications in wireless systems due to their superior performance,low cost, compact area, and fabrication compatible characteristics. A comprehensive review on their reconfigurability and broadband application has been presented in this paper. It is also proposed that the on-chip micro strip patch antenna structure and model include the matching circuit in PCB structure which ensures the impedance matching of high-frequency components in turn improves the maximum transfer of power between the antenna and the transmitter/receiver circuitry. Additionally, it has been shown that on-chip integration of SPST switch have manifested the performance of the patch antenna in terms of reconfigurability with the gain of 2.2dBi at 54.5% bandwidth efficiency in 0.18 CMOS FD-SOI technology for linearly polarized pattern.

I. INTRODUCTION

New emerging applications in wireless communications require advanced antenna systems that are able to satisfy the needs of such applications. Reconfigurable antennas appear to offer a solution that allows the integration of multiple radios into a single platform. The integration of multiple radios with reconfigurable antennas maximizes connectivity without resorting to multiple antenna components. The ability of reconfigurable antennas to change their functionality on demand allows them to dynamically cater for multiple wireless services without increasing the real estate required to accommodate multiple antennas. The new era of antenna design must generate antennas that are cognitive and adjust to the environment and ever-changing surrounding conditions. Also, there is a need for antennas that can overcome failures and swiftly respond to new developments.

Cognitive radio, multiple input multiple output (MIMO) channels, on-body networks, satellites, and space communication platforms are all possible applications for the integration of highly versatile, reliable, and efficient reconfigurable antennas. In this section, the design of reconfigurable antennas that are proposed to service different practical wireless communication applications is discussed.

An antenna design can be made reconfigurable by utilizing various reconfiguration techniques such as switches or mechanical actuators. The most widely reconfigured antenna type is the microstrip antenna, where the integration of reconfiguring components into the antenna structure becomes part of the antenna design process. Typically, a reconfigurable patch antenna consists of a number of separate metalized regions that lie on a plane and are connected together using tuning components presented by Costantine et al. 2013c [1]. By dynamically controlling the state of the tuning components, the different metalized sections can be activated in a very selective way, thus altering the radiation performance of the total antenna. In general, every reconfigurable antenna design starts with a predetermined objective that aims to satisfy the existing technical constraints. However, every antenna engineer targets a certain antenna property to reconfigure. An example of such property can be frequency of operation, radiation pattern, and/or polarization. Once this property is determined, the designer works to achieve this objective by rearranging the different antenna components correspondingly.Q-band on-chip antennas with high gain and wide band have been investigated by many researchers for SoC applications. In [2], CMOS SOI (silicon on insulator) technology with highresistivity (HR) silicon substrate has been used to improve the antenna gain to -1.8 dBi. In [3], an on-chip H-slot is designed to excite a high-permittivity dielectric resonator (DR).

This is glued on the antenna chip. With this off-chip DR, the measured gain of this antenna has achieved 1 dBi. Additionally, a triangle patch antenna is realized by the standard CMOS process in [4]. This antenna is designed to meet the Q-LINKPAN standard requirement. It has a favorable bandwidth from 40 to 50 GHz with a simulated gain of 1.5 dBi at 45 GHz.

II. RECONFIGURABILITY IN PATCH ANTENNA

Reconfigurable antennas can be assembled into various groups based on the properties of each reconfiguration (Costantine et al. 2013c). These groups are arranged as follows:

Group 1: Frequency reconfigurable antennas Antennas under this group can change their frequency of operation based on the user's demand. They reconfigure their operation to function in multiple frequency bands. Such antennas are widely useful in wireless communication applications.that require a change in operating frequencies and to switch from one channel into another. Cognitive radio is an example application for this antenna group.

Group 2: Radiation pattern reconfigurable antennas Antennas under this group can change their radiation pattern while maintaining a fixed frequency of operation. These antennas reshape their radiation patterns to block a signal or to allow radiation in a certain predetermined direction. Mobile antenna systems can be proposed as examples of such antenna group.

Group 3: Antennas with reconfigurable polarization Antennas under this group can change their polarization type while maintaining their fixed frequency and radiation pattern. These antennas reshape their radiation characteristics to exhibit multiple polarization schemes. MIMO (multiple input multiple output) channels are application examples of such antenna group.

Group 4: Antennas with hybrid reconfiguration techniques Antennas under this group can simultaneously change multiple characteristics in their operation. These antennas can, for example, change their operating frequency as well as their polarization scheme for each frequency of interest.

They can also reshape their radiation pattern while changing their operating frequencies or polarizations. Achieving the required reconfiguration functionality requires an appropriate selection of the reconfiguration mechanism that will achieve the desired functionality or property. A reconfiguration mechanism is selected to satisfy imposed constraints whilecompleting the antenna design task efficiently. There are numerous reconfiguration techniques that can be incorporated into the antenna design in

As a summary, an antenna designer applies a reconfiguration technique to any antenna structure and thus transforms it into a reconfigurable antenna. The application of an appropriate reconfiguration technique allows the implementation of the corresponding antenna in a practical wireless communication application that requires an adaptive RF front-end. The cost of adding reconfigurability to the antenna behavior can be determined as a function of multiple factors (Christodoulou et al. 2012 [5]) as discussed below: (a) Factor 1: A complexity is added to the antenna structure due to the presence of biasing networks that are required to control the state of the reconfiguration components. (b) Factor 2: The incorporation of active components results in increased power consumption. (c) Factor 3: Undesired effects such as generation of harmonics due to the addition of nonlinear active components. (d) Factor 4: The speed of the reconfiguration leading to the required functionality.

A MIMO communication system is based on the need for multiple antennas that are installed at both sides of the communication channel. The purpose of such installation is to enable the communication channel to transmit and receive multiple signals at the same time. This ability increases the spectral efficiency and capacity, thus overcoming issues such as multipath and fading. On the other hand, a large improvement over the channel capacity can be achieved by incorporating reconfigurable antennas that exhibit a reconfiguration in their radiation patterns and polarizations (Cetiner et al. 2004 [6]; Piazza et al. 2008 [7]; Li et al. 2009 [8]; Grau et al. 2010 [9]; Qin et al. 2010a [10]; Christodoulou et al. 2012 [5]). As an example, an antenna shown in Fig. 1 (Quin et al 2012 [11]) exhibits a reconfigurable radiation pattern. The antenna is a microstrip U-slot patch antenna that uses eight PIN diodes to achieve pattern reconfiguration.
Eight shorting posts are implemented around the patch to change the operating mode of the antenna

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frommonopolar patch mode to normal patch mode (Quin et al 2012). The two modes of operation are designed to operate in similar frequency ranges.

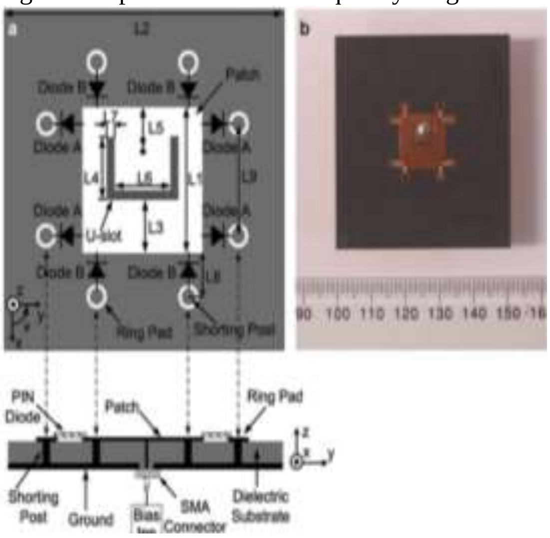

Fig. 1 Antenna with reconfigurable radiation pattern (Quin et al. 2012)

The proposed antenna can electrically reconfigure the radiation pattern between conical and bore-sight patterns with an overlapping impedance bandwidth. Four antenna elements with the same design concept are then employed in a 2 x 2 MIMOOFDM prototype. The capacity results are compared with omnidirectional antennas, and channel capacity enhancements are witnessed in both line-of-sight and non-lineof-sight indoor environments (Quin et al 2012 [11]). Another example of an antenna designed for MIMO channels is an electronically steerable passive array radiator (ESPAR). This antenna shown in Fig. 2 (Zhou et al. 2014 [12]) consists of one driven monopole in the center surrounded by a ring of six uniformly spaced (quarter wavelength spacing) parasitic monopoles.

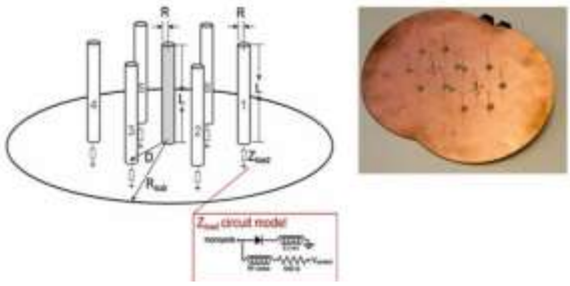

Fig. 2 Proposed and fabricated ESPAR for MIMO communications (Zhou et al. 2014 [12])

Each parasitic element is terminated with a load that consists of a 0.3 nH inductor and a PIN diode. This load is essential to provide the reactance required to either make the monopole a director when it is inductive or a reflector when it is capacitive (Zhou et al. 2014).

III. RECONFIGURABLE ANTENNAS FOR COGNITIVE RADIO APPLICATIONS

A cognitive radio requires antenna systems that have the ability to identify **changes in a communication setting** and be able to react accordingly. Cognitive radio is basedon the concept of monitoring a channel and searching for unused spaces in the spectrum. Once unused spaces are identified, a reconfigurable antenna is activated to tune its operation to broadcast, thus increasing the communication efficiency (Tawk et al. 2014a [13]). Channel sensing can be achieved through a wideband antenna or a reconfigurable narrowband antenna. The communication process on the other hand requires a reconfigurable antenna to be able to change its operation in order to manage the dynamically discovered white spaces in the spectrum. A cognitive radio device's operation is based on a cycle which starts by observing the channel activity, which is achieved by a sensing (wideband) antenna. In the second step of the cycle, a cognitive processor decides which part of the spectrum is suitable for communication. The processor next activates the communicating antenna to achieve the required mode of communication. In the last step, the processor achieves cognition by learning from previous channel activities.

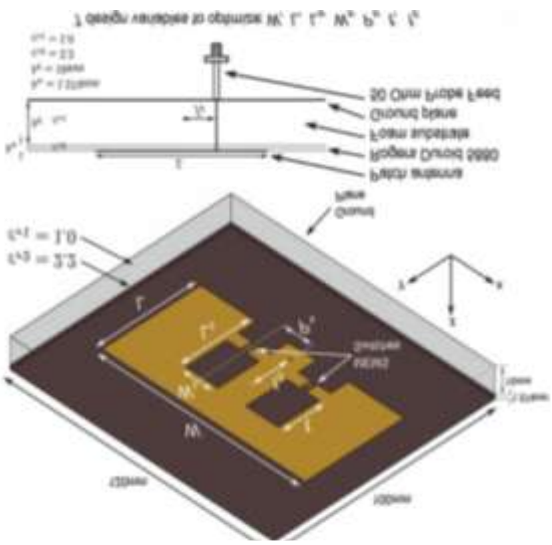

Fig. 3 Patch implementation on a cognitive radio platform.

This cycle allows the cognitive radio device to self-decide and optimally self-reconfigure its hardware in order to realize the selected mode of communication (Jayaweera and Christodoulou 2011

[14]; Tawk et al. 2014a). Multiple reconfigurable antenna designs are presented in literature for implementation on a cognitive radio platform. An example of such antennas is the one shown in Fig. 3 (Rajagopalan et al. 2014). The antenna presented is a frequency reconfigurable E-shaped patch antenna that provides wideband frequency switching using MEMS. The antenna is proposed for applications on cognitive radio platforms with large terminals such as laptops or as an array element (Rajagopalan et al. 2014). The presented E-shaped patch offers a simple single-layer, singgle-feed structure with a wide instantaneous bandwidth (Rajagopalan et al. 2014 [15]).

Various antenna systems can be proposed for cognitive radio applications (Tawk et al. 2014b [16]). However, it is critical to understand that adding cognition to antenna systems and allowing them to communicate over unused frequency gaps do not solve all other issues in the spectrum. Hence, it is important to design antennas that address spectrum concerns such as fading or multipath in a cognitive radio setup. A MIMO-based antenna can be proposed for cognitive radio applications as shown in Fig. 4 (Tawk et al. 2014b [16]).

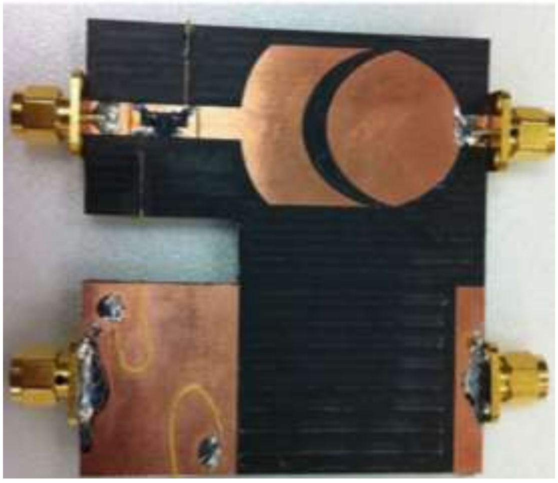

Fig. 4 MIMO-based reconfigurable filtenna (Tawk et al. 2014b)

The reason behind adopting a MIMO-based antenna for cognitive radio is to combat fading, ensure reliable communication between the end users, and improve spectrum usage efficiency.

Another MIMO-based reconfigurable cognitive radio antenna is shown in Fig. 5 (Hussain and Sharawi 2015 [17]). The antenna system design is based on a compact meandered line planar reconfigurable two-element MIMO system. The antenna system is made tunable in different bands using PIN and varactor diodes. The antenna operates at lower frequency bands starting from 580 to 680 MHz and from 834 to 1,120 MHz. The important feature of the proposed design is that the reference ground plane of the reconfigurable antenna is optimized to work as a sensing antenna to scan the frequency spectrum while operating as a ground plane for the reconfigurable antenna during the communication stage (Hussain and Sharawi 2015 [17]).

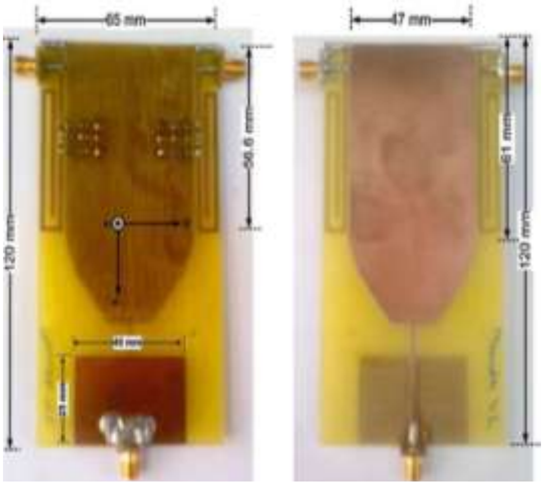

Fig. 5 Front and back view of the proposed MIMO-based reconfigurable cognitive radio antenna system (Hussain and Sharawi 2015)

IV. ON-CHIP SWITCHES DESIGN

In this work, two of the same single-pole single-throw (SPST) switches are designed for tuning the antenna resonance frequency. The switch schematic with its small-signal equivalent circuit is presented in Fig. 6. By examining Fig. 6(a), one can see that this switch is implemented by an N-type field-effect transistor (NFET). The switch state control voltage (Vctrl) is applied to the gate of this NFET. Meanwhile, a resistance R1 (15 kΩ) is connected in series at the NFET's gate, to isolate the AC signal and the control port. The source and the drain of the NFET are used to connect two parts of the antenna together.Two grounded resistances R2 (15 kΩ) and R3 (15 kΩ) are connected in parallel to the source and drain, respectively, for the purpose of pulling down the voltage to low at these two ports.

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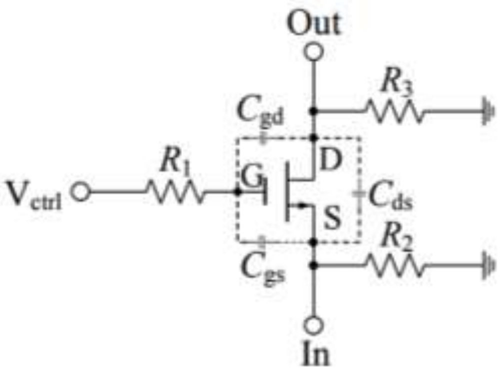
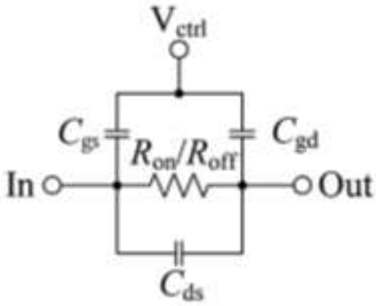
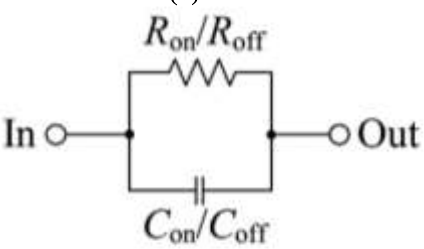


(a)



(b)



(c)

Fig. 6 The proposed SPST switch: (a) Schematic. (b) Small-signal equivalent circuit. (c) Simplified small-signal equivalent circuit.

Then, when Vctrl changes from high (1.5 V) to low (0 V), the state of the switch will change from on to off correspondingly. It is worthwhile mentioning that the parasitic capacitances, including the capacitance between the gate and the source (Cgs), the capacitance between the gate and the drain (Cgd), as well as the capacitance between the drain and thesource (Cds), must be taken into account in the design of switch, especially in the millimeter wave band. The small-signal equivalent circuit of the proposed switch is illustrated in Fig. 6(b). The on/off-resistance R_{on}/R_{off} represents the NFET in the state of on and off, respectively.

The parasitic capacitances Cgs, Cgd, and Cds are all included in this equivalent model and they can be simplified as one capacitance C_{on} or C_{off}, as shown in Fig. 6(c). The Ron,Roff, C_{on}, and C_{off} can be expressed as:

$$\mathbf{R_{on} = r_{on}/W,\ R_{off} = 6.5k\Omega \quad (1)}$$

$$\mathbf{C = c.W,\ C_{on} = c_{on}.\ W \quad (2)}$$

where W, ron, con, and coff represent the gate width of the NFET, the on-resistance, and the on/off-capacitance per unit transistor width, respectively [18]. For the 0.18-µm CMOS SOI process, the simulated ron, coff, and con are around 380 Ω·µm, 0.32 fF/µm, and 0.51 fF/µm, respectively. The Roff is not related to the gate width of the transistor and is simulated around 6.5 kΩ. Using this simplified model of switch, the simulated gain (simulated at 45 GHz) and bandwidth of the proposed antenna versus the transistor gate width have been studied, as illustrated in Fig. 7.

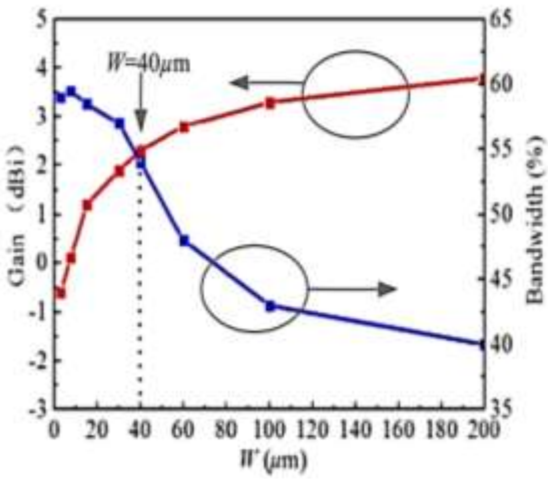


Fig. 7 Simulated gain and bandwidth of the proposed antenna versus the NFET gate width (W) of the on-chip switches.

It shows that, with the increase in W, the antenna gain will be increased and the antenna bandwidth will be reduced accordingly. This is because a larger W results in a smaller Ron according to (1). A lower energy will be consumed by this on-chip switch and then higher antenna efficiency will be achieved. However, according to (2), increasing W results in a bigger Coff. It implies that the on-chip switch with a bigger Coff has a lower isolation and then the variation range of the antenna effective length that can be obtained by changing the state of the switches will become narrow. As a result, the antenna bandwidth improved by this on-chip switch will become limited.

So, the key work in the switch design is to choose a reasonable W to compromise the gain and the bandwidth of the antenna. According to Fig. 7, one can see that the curves of gain and bandwidth have an intersection when W is around 40 µm and an attractive gain of 2.2 dBi and bandwidth of 54.5% can be obtained at the same time. So, in this work, W

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is set to 40 µm by compromise, with the Ron, Con, and Coff being 9.5 Ω, 20.4 fF, and 12.8 fF, respectively. Furthermore, according to the current distribution, it is known that the antenna is linearly polarized.

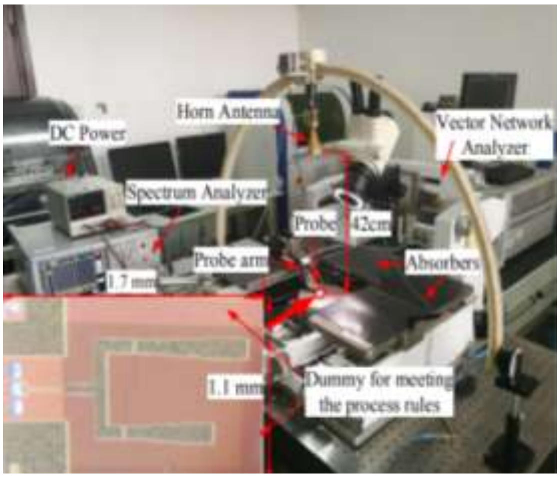

Fig. 8. Manufactured antenna and measurement setup.

Fig. 8 shows the measurement setup and the die micrograph of the manufactured antenna. To comply with the design rules imposed by the foundry, dummy fills are buried around the antenna in both M2 and MT layers. Fortunately, the impact of these fills on the antenna performance can be ignored as [18] has reported.For the radiation pattern test, the signal is generated by the VNA, and is transmitted by the antenna under test (AUT). Then, the signal is received by a horn antenna, and its power level is displayed on the spectrum analyzer. The antenna gain is calculated based on

$$\mathbf{G_t = P_r - P_t - 20.\log(\lambda o/4\pi R) - G_t + L_{cables} + L_{probe} + L_{transition}} \quad (3)$$

which is evolved from the Friis transmission formula, as reported in [19, 20]. In this formula, Pr is the receiving power, Pt is the transmitting power, λ0 is the wavelength in the air, R is the distance between the AUT and the receiving antenna,Gt is the gain of the AUT, and Gr is the gain of the receiving antenna.

Lcables, Lprobe, and Ltransition represent the loss of coaxial cables, the loss of GSG probe, and the loss of waveguide-to-coaxial transition, respectively. The Lprobe can be measured using the "three-gamma method" for the improvement of the measurement accuracy [20, 21, 22].

V. CONCLUSION

For Q-band applications, a broadband on-chip frequency reconfigurable antenna with on-chip switches is presented in addition to the comprehensive review on reconfigurability of modern patch antennas for cognitive radio systems. Based on the small-signal equivalent circuit of the switch, the influence of the gate width of the switch transistor on the gain and bandwidth of the proposed antenna has been studied. An optimized gate width of 40 µm is used in this design. With these switches, the proposed antenna obtains an attractive -10 dB impedance bandwidth of 21.5 GHz, which corresponds to 53.4% at the center frequency of 40 GHz. Meanwhile, the proposed antenna has a measured peak gain of 3.3 dBi at 45 GHz. A reasonable agreement between the simulation and measurement results has been observed in this work. It indicates that the proposed simulation model of the on-chip antenna and particularly the model of the on-chip switch are generally reliable.

Acknowledgements
We (Authors) would like to thank the Integral Information and Research Centre of Integral University, Lucknow, India for providing an opportunity to carry out this research work. This work is an intellectual property of Integral University.

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