Three-Stacked Dielectric Ring Resonator Loaded Hybrid Monopole Antenna for Improved Ultrawide Bandwidth

Ali A. Al-Azza [1], Nuhad A. Malalla [2], Mohamed M. Morsy [3], and Frances J. Harackiewicz [4]

[1] Department of Electrical Engineering, College of Engineering
University of Basrah, Basra, Iraq
alieng@siu.edu

[2] Department of Chemical and Petroleum Refining Engineering, College of Oil and Gas Engineering
Basra University for Oil and Gas, Basra, Iraq
nuheng@siu.edu

[3] Electrical Engineering Department
Texas A&M University-Texarkana, Texarkana, TX 75503, USA
mmorsy@tamut.edu

[4] Department of Electrical and Computer Engineering
Southern Illinois University Carbondale, Carbondale, IL 62901 USA
fran1@siu.edu

Abstract **—** In this paper, a new wideband and compact three-segment composite dielectric ring resonator (DRR) antenna excited by an axi-symmetric coaxial monopole has been introduced. The proposed antenna has been investigated numerically and experimentally for enhanced impedance bandwidth. At the lowest operating frequency, the presented antenna has a footprint area of just $0.16\boldsymbol{\lambda_o}$ x $0.16\boldsymbol{\lambda_o}$. According to the measurement results, the antenna offers a fractional impedance bandwidth equal to 159% with 8dBi peak gain. The antenna provides symmetrical and stable monopole like radiation pattern over the entire impedance bandwidth. With such performance, the suggested antenna can be usefully employed in different wideband applications such as electromagnetic interference (EMI) and defense applications.

Index Terms **—** Dielectric resonator, hybrid monopole antenna, wideband antenna.

I. INTRODUCTION

Designing an ultra-wideband monopole antenna with stable radiation patterns by using an electric monopole (MP) with dielectric ring resonator (DRR) has received great interest from researchers. The first research study in this field was made in 2002 by researchers from Canada by experimentally studying a configuration of a MP loaded by an annular DRR [1] which showed a simulated impedance bandwidth of 100% [2]. Such wideband behavior was due to the excitation of three resonant modes. The lowest and highest resonance frequencies are generated by the MP and the excitation of the $TM_{01\delta}$ mode of the DRR, respectively. While the coupling between the MP and DRR is responsible for generation of the intermediate resonance. A useful design guideline for the wideband MP-DRR antenna was developed by Guha et al. [3]. After that, many research groups developed several hybrid configurations of an electric monopole and a DRRs over a period of time [4-10]. The impedance bandwidth was enhanced to 110% in [4] by using inverted cone-shaped DRR. Similar impedance bandwidth in [4] was reported in [5] but by using a MP with a configuration of 'T'-like shape. In [6], a pawn-like shape DRR has been explored by stacking a conical and hemispherical ring. Impedance bandwidth of about 122% was obtained by using such configuration. Table 1 summarizes the chronology of bandwidth enhancement of hybrid monopole antenna. Till the date, the maximum reported impedance bandwidth being 137-140% [8-10].

In this paper, three-segment composite dielectric ring resonator are stacked and excited by a coax-fed cylindrical monopole. The proposed antenna exhibits an ultra-wide impedance bandwidth compared to earlier studies in the literature as listed in Table 1. About 159% (8.6:1) fractional bandwidth is experimentally obtained with a constant monopole like radiation over the entire frequency range. The simulation study of antenna has been performed through Computer Simulation Technology (CST) which is a 3D electromagnetic

Submitted On: February 7, 2020
Accepted On: April 4, 2020

simulation software. Details of the proposed antenna design and simulated current distributions are discussed. The prototype of the antenna has been fabricated and tested. The measured results are compared with the simulated ones and a good agreement is revealed.

Table 1: Reported bandwidth enhancement techniques of hybrid monopole antenna

Structure Investigated	**Year**	**DRR Unit**	**No. of Resonances**	**Ratio (Percent BW)**
Annular ring DR excited by electric monopole [2]	2005	1	3	3:1 (100%)
Inverted conical DRA loaded monopole [4]	2008	1	4	3.5:1 (111%)
Annular DRA excited by T-shaped monopole [5]	2008	1	4	3.5:1 (112%)
Pawn shaped DRA loaded monopole [6]	2009	2	4	4:1 (122%)
Hemispherical/conical DR loaded monopole [7]	2012	1	4	4.2:1 (126%)
Stacked conical ring DR loaded monopole [8]	2013	2	5	5.4:1 (138%)
Stacked annular ring DR [9]	2014	2	6	5.6:1 (140%)
Three-segment composite DR [10]	2017	3	6	5.4:1 (137%)
Proposed design	-	3	9	8.6:1 (159%)

II. ANTENNA GEOMETRY AND DESIGN

The design clue of the proposed composite antenna has been extracted from the earlier studies [3], [8] as depicted in Fig. 1. By placing an annular ring on the top of two stacked conical DRs, the operating bandwidth is enhanced as a result of increased number of resonance modes. The proposed antenna introduces nine monopole-like resonances, which is four additional resonances above those provided by [8]. The details of the antenna configuration are given are in Fig. 2. The probe of the Pasternack's PE4434 commercial SMA connector is used as a cylindrical MP with a radius (r) equal to 0.65 mm. The coaxial feed and the MP share the same rotational axis of symmetry (the z-axis). The value of MP length (ℓ) can be determined as $\ell = \lambda_1/4$, where λ_1 is the wavelength at the corresponding dominant mode of the monopole. The MP is loaded by three vertically stacked annular dielectric elements. All DRs are made up by using Eccostock ceramic based dielectric material with permittivity equal to 10. Selecting a material with higher dielectric constant could degrade the bandwidth and the radiation of the antenna as discussed in [7]. A cylindrical hole of radius R_h is drilled through the center of the three DRs. The value of the coupling between the MP and the stacked DR elements is determined by the spacing distance of the air gap between the MP surface and the internal face of DRR structure. Spacing parameter can be determined as $s = R_h - r$. The overall performance of the antenna can be deteriorated with higher values of s. The best choice for the parameter s is selected according to $r < s < 2r$.

A copper plate with dimensions of 40×40 mm^2 and a thickness of 3 mm is used to place the designed antenna.

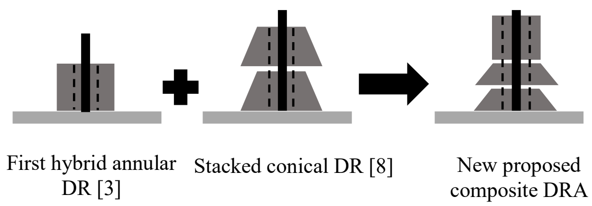


Fig. 1. Proposed antenna configuration as a combination of other design shapes.

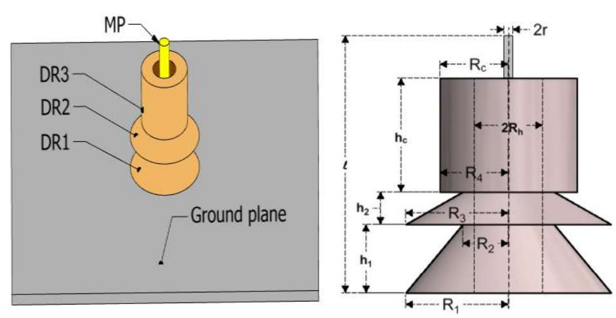


Fig. 2. Proposed antenna configuration.

The base radius of conical dielectric resonator is selected according to:

$$R_1 = 47.713 \times \mathrm{Re}(K_o a)/f_r\ , \qquad (1)$$

where R_1 is in millimeter, and f_r is in GHz which is the mid frequency between the fundamental resonant frequency of quarter wave MP and the first higher resonant mode of MP due to the conical DR. Re$\{K_o a\}$ is the real part of the $K_o a$, and its value depends upon the permittivity of the DR [7] as shown in Table 2.

Table 2: $\mathrm{Re}(K_o a)$ of the dr resonant mode with respect to permittivity

ε_r	$Re(k_o a)$	ε_r	$Re(k_o a)$	ε_r	$Re(k_o a)$
2	3.182	25	0.842	60	0.567
4	2.246	30	0.779	65	0.546
6	1.834	35	0.728	70	0.527
8	1.588	40	0.685	75	0.510
10	1.420	45	0.649	80	0.494
15	1.160	50	0.618	85	0.480
20	0.922	55	0.591	90	0.467

By using the hemispherical counterpart of the conical DR, its height can be calculated as $h = \sqrt{R_1^2 - R_h{}^2}$.

The height and radius of the cylindrical DR can be estimated as [3]:

$$0.4\ell_t \leq h_c \leq 0.5\ell_t$$
$$R_c = R_h\,/0.3\ , \qquad (2)$$

where ℓ_t is the value of the MP length starting from the base of the cylinder to the top end of MP.

To improve the impedance bandwidth, an extensive parametric study is performed to select and tune the parameters of the antenna. Table 3 lists the finally optimized dimensions of the proposed antenna.

Table 3: Geometry details in millimeters of the proposed antenna

Physical Dimension	Value
Cone1 (Base radius R_1, Top radius R_2, height h_1)	(4.5, 2, 3)
Cone2 (Base radius R_3, Top radius R_4, height h_2)	(4.5, 2, 1.42)
Cylinder (radius R_c, height h_c)	(3, 5)
Inner radius of DRs (R_h)	1.5
Monopole radius (r)	0.65
Monopole length (ℓ)	12

III. SIMULATIONS AND MEASUREMENTS

All nine distinct resonances of the antenna are individually studied to investigate the operation principle of the antenna. Figure 3 shows the magnitude of the reflection coefficient characteristics of MP alone, DRR alone, and the suggested antenna. The MP loading effect with different dielectric elements is also studied and depicted in Fig. 4. The fundamental and the first higher order mode resonances of the monopole occur at 5.7 GHz (ℓ =λ/4) and 16 GHz (ℓ =3λ/4), respectively as shown in Fig. 3. The intermediate resonances which occurs at around 10.3 GHz and 13 GHz are due to the loading effect of the cylindrical DR as it is clearly observed in Fig. 4. The dielectric configuration loads the MP in such a way that the MP has effective length (ℓ_{eff}) less than the actual length at these two frequencies. Additional two resonances are identified at 24 GHz and 35 GHz. The fundamental $TM_{01\delta}$ resonance of the DR is clearly observed at 24 GHz. While a higher order mode is present in the DR configuration at 35 GHz. Third and fourth higher modes of the MP are observed at 30 GHz (ℓ =5λ/4) and 38 GHz (ℓ =7λ/4), respectively. Finally, an extra resonance is obtained at 43 GHz where the MP height is approximately a complete wavelength.

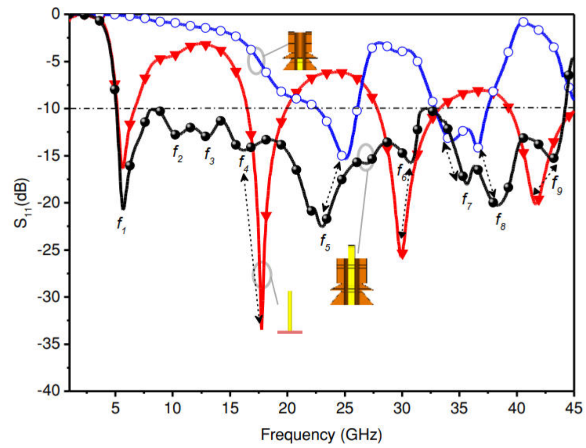


Fig. 3. Magnitude of the reflection coefficient of: MP, DRs excitation only, and proposed antennas.

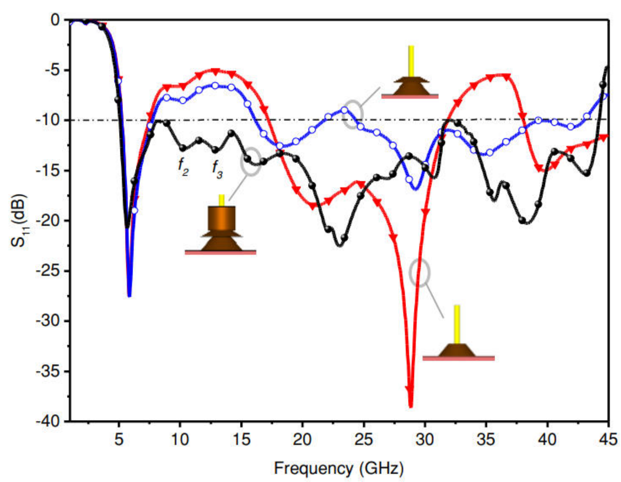
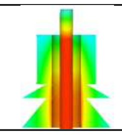
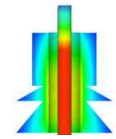
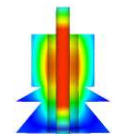
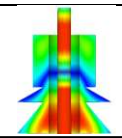
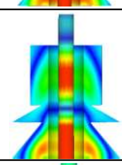
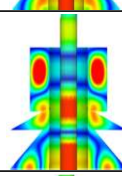
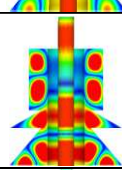
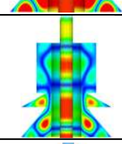
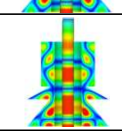


Fig. 4. MP loading effect with different blocks of DR.

Table 4 lists the observations of the magnetic field distributions for all nine resonant frequencies which clearly support the explanations that concluded from the magnitude of the reflection coefficient response of the antenna.

Table 4: Identification the nature of resonant modes in the proposed antenna

Resonances	Frequency (GHz)	Observations	Magnetic Field Distributions
1st (f_1)	5.7	Excitation of a quarter wave MP	
2nd (f_2)	10.3	Excitation of a quarter wave MP with ℓ_{eff}= 0.8ℓ	
3rd (f_3)	13	Excitation of a quarter wave MP with ℓ_{eff}= 0.6ℓ	
4th (f_4)	16	1st higher order mode of MP	
5th (f_5)	24	TM_{01} mode in DRs	
6th (f_6)	30	2nd higher order mode of MP	
7th (f_7)	35	1st higher order mode of DRs	
8th (f_8)	38	Weak 2nd higher order mode $TM_{02\delta}$ of DRs	
9th (f_9)	43	3rd higher order mode of MP	

The proposed antenna was fabricated to corroborate the simulated results. Figure 5 shows the photograph of fabricated antenna. To measure the fabricated antenna, HP 8510C vector network analyzer has been calibrated over the frequency range from 4 GHz to 45 GHz to observe the impedance bandwidth response of the antenna. Synthetic adhesive is used to fasten the DR structure on the metal plane. Figure 6 shows the measured and simulated magnitude of the reflection coefficient characteristics of the antenna indicating a close agreement between them. About 159% measured bandwidth centered at 24 GHz is achieved, indicating more than 8.6:1 ratio bandwidth. Compared to all previous published works that mentioned in Table 1, the presented antenna offers the widest impedance bandwidth.

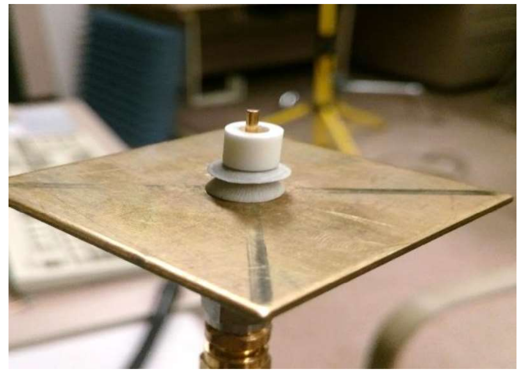


Fig. 5. Prototype fabricated antenna.

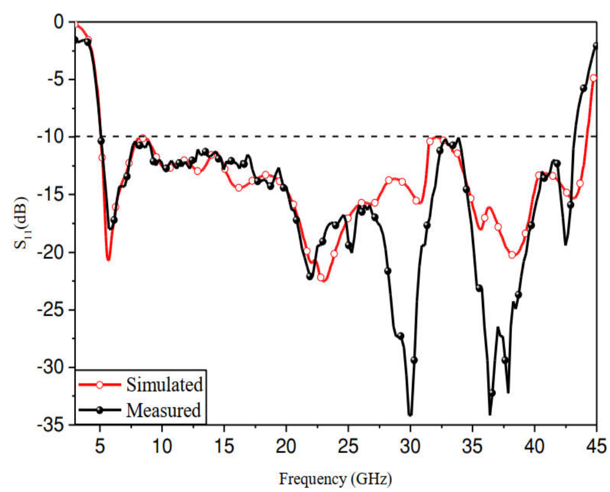


Fig. 6. Simulated and the measured magnitude of the reflection coefficient for the proposed antenna.

The radiation patterns of the antenna at different resonant frequencies covering the entire band are shown in Fig. 7. A single vertical plane (*xz*-plane) is used to investigate the radiation characteristics of the antenna since the antenna has vertical symmetrical configuration. Generally, radiation patterns of wideband antennas are varying with the operating frequency. However, and as it can be noticed in Fig. 7, the monopole-type radiation pattern is evident over the entire impedance bandwidth with a maximum gain of 7.8 dBi. The radiation patterns are measured at 5.7 GHz and 10.3 GHz and compared with the simulated ones as shown in Fig. 8, and a good mutual agreement is revealed.

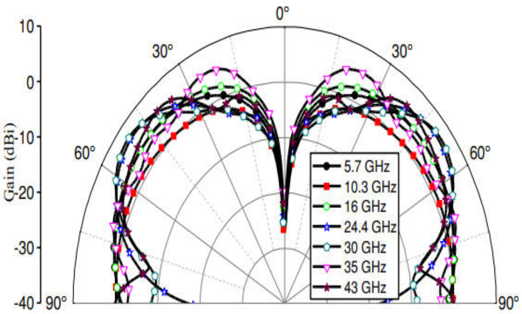
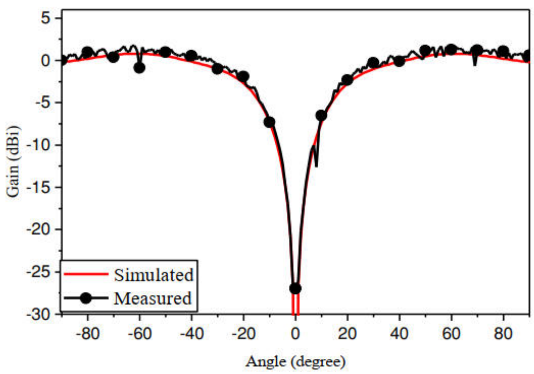
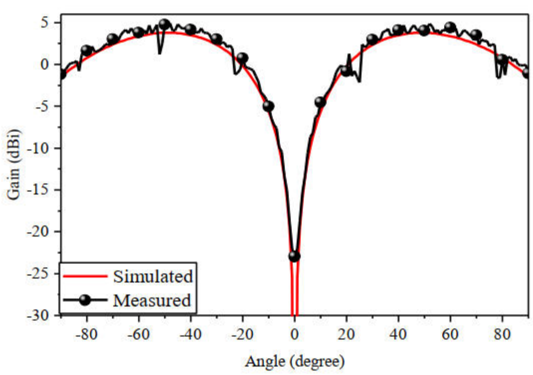


Fig. 7. Gain patterns of the proposed antenna along the xz-plane at different frequency points.



(a)



(b)

Fig. 8. Radiation field pattern for the antenna under test obtained at: (a) 5.7 GHz and (b) 10.3 GHz.

IV. CONCLUSION

A wideband hybrid monopole antenna has been proposed and investigated. The operational concept of the antenna was described, and its performance for ultra-wideband wireless applications was examined. The antenna has been fabricated and tested to validate its computed performance. The measured results indicate that the proposed antenna recorded the highest bandwidth value achieved so far of about 159%, covering a frequency from 5 to 43 GHz along with consistent radiation pattern and peak gain of 7.8 dBi. With such performance, the proposed antenna can be utilized for wide range of applications such as ultra-wideband communications and EM wideband sensor.

REFERENCES

[1] A. P. A. Ittipiboon and S. Thirakoune, "Bandwidth enhancement of a monopole using dielectric antenna resonator loading," in *Proc. ANTEM Conf.*, pp. 387-390, 2002.

[2] M. Lapierre, Y. M. M. Antar, A. Ittipiboon, and A. Petosa, "Ultra wideband monopole/dielectric resonator antenna," *IEEE Microwave and Wireless Components Letters*, vol. 15, pp. 7-9, 2005.

[3] D. Guha, Y. M. M. Antar, A. Ittipiboon, A. Petosa, and D. Lee, "Improved design guidelines for the ultra wideband monopole-dielectric resonator antenna," *IEEE Antennas and Wireless Propagation Letters*, vol. 5, pp. 373-376, 2006.

[4] M. N. Jazi and T. A. Denidni, "A new hybrid skirt monopole dielectric resonator antenna," in *2008 IEEE Antennas and Propagation Society International Symposium*, pp. 1-4, 2008.

[5] S. Ghosh and A. Chakrabarty, "Ultrawideband performance of dielectric loaded T-shaped monopole transmit and receive antenna/EMI sensor," *IEEE Antennas and Wireless Propagation Letters*, vol. 7, pp. 358-361, 2008.

[6] D. Guha, B. Gupta, and Y. M. M. Antar, "New pawn-shaped dielectric ring resonator loaded hybrid monopole antenna for improved ultrawide bandwidth," *IEEE Antennas and Wireless Propagation Letters*, vol. 8, pp. 1178-1181, 2009.

[7] D. Guha, B. Gupta, and Y. M. M. Antar, "Hybrid monopole-DRAs using hemispherical/conical-shaped dielectric ring resonators: Improved ultrawideband designs," *IEEE Transactions on Antennas and Propagation*, vol. 60, pp. 393-398, 2012.

[8] C. Ozzaim, F. Ustuner, and N. Tarim, "Stacked conical ring dielectric resonator antenna excited by a monopole for improved ultrawide bandwidth," *IEEE Transactions on Antennas and Propagation*, vol. 61, pp. 1435-1438, 2013.

[9] C. Ozzaim, "Monopole antenna loaded by stacked annular ring dielectric resonators for ultrawide bandwidth," *Microwave and Optical Technology Letters*, vol. 56, pp. 2395-2398, 2014.

[10] D. Guha, D. Ganguly, S. George, C. Kumar, M. Sebastian, and Y. M. M. Antar, "A new design approach for a hybrid monopole to achieve increased ultrawide bandwidth [Antenna Designer's Notebook]," *IEEE Antennas and Propagation Magazine*, vol. 59, pp. 139-144, 2017.

Ali A. Al-Azza received the B.S. and M.S. degrees in Electrical Engineering from Basrah University, Iraq in 2005 and 2008, respectively. In 2016, he received Ph.D. degree in Electrical and Computer Engineering from Southern Illinois University, Carbondale, IL. Since 2017, he has been an Instructor with the Electrical Engineering Department, Basrah University, Basra, Iraq. He is the author of more than 18 peer-review research papers. His research interests include electromagnetic devices, antennas, RF filters, and dielectric resonators (DR), evolutionary optimization techniques.

Nuhad A. Malalla received the B.S. and M.S. degrees in Electrical Engineering from Basrah University, Iraq in 2005 and 2008, respectively. In 2016, she received Ph.D. degree in Electrical and Computer Engineering from Southern Illinois University, Carbondale, IL. Since 2018, she has been an Instructor with the Department of Chemical Engineering and Petroleum Refining Engineering, College of Oil and Gas Engineering, Basrah University for Oil and Gas. Her research interests include electromagnetic devices, imaging techniques, antennas, control methods, and dielectric resonators (DR), and optimization.

Mohamed Morsy received the B.S. degree in Electrical Engineering from Alexandria University, Egypt in 2004 and the M.S. and Ph.D. degrees in Electrical and Computer Engineering from Southern Illinois University, Carbondale, IL, in 2006 and 2010; respectively. Since 2018, he has been an Associate Professor with the Electrical Engineering Department, Texas A&M University-Texarkana, Texarkana, TX. He is the author of more than 20 peer-review articles. His research interests include electromagnetic devices, antennas, RF filters, and dielectric resonators (DR). Other subjects of research are on designing antennas for the 4/5G- mobile terminals, and phased array antennas. Morsy is an IEEE senior member and an IDEAL (Institute for the Development of Excellence in Assessment Leadership) scholar.

Frances J. Harackiewicz received B.S., M.S., and Ph.D. degrees in Electrical Engineering from University of Massachusetts Amherst, in 1984, 1986, and 1990, respectively. She has more than 30 peer-review papers. Her research interests include electromagnetics, antenna theory and design, microwaves, microstrip phased arrays and anisotropic materials, small multiband and broadband antennas, PIFAs, loops, printed and dielectric antennas.

Harackiewicz is senior, IEEE (Institute of Electrical and Electronics Engineers, Inc.). She is also member, WEPAN (Women in Engineering Programs & Advocates Network). She is Counselor of SIUC Student Branch of the IEEE Advisor, SIUC Student Chapter of Engineering Honor Society Tau Beta Pi.