DOI: 10.21917/ijme.2025.0351

CO-DESIGN OF FLEXIBLE RF/ANTENNA SYSTEMS FOR EFFICIENT WIRELESSLY POWERED BACKSCATTER COMMUNICATION PLATFORMS

Ravi M. Yadahalli[1] and Balachandra Pattanaik[2]
[1]Department of Electronics and Communication Engineering, Methodist College of Engineering and Technology, India
[2]School of Electrical and Computer Engineering, Wollaga University, Ethiopia

Abstract

Backscatter communication has emerged as a key enabling technology for ultra-low-power and batteryless wireless platforms, especially in the context of the Internet of Things (IoT) and pervasive sensing systems. Traditional designs often treat the antenna and RF circuitry independently, leading to suboptimal performance due to impedance mismatches, low energy harvesting efficiency, and poor communication reliability. Flexible materials and novel antenna structures have gained attention for wearable, implantable, and conformal applications but face challenges in maintaining performance consistency under mechanical deformation. This paper proposes a co-design methodology for flexible RF/antenna systems to optimize energy harvesting and communication efficiency in wirelessly powered backscatter communication platforms. The method integrates the antenna and RF front-end design to ensure impedance matching, maximize power transfer, and enable flexible operation. A meandered dipole antenna integrated with a Schottky-diode-based rectifier is designed using flexible polyimide substrate. The design ensures mechanical flexibility while achieving high RF-DC conversion efficiency. Simulations using CST Microwave Studio and co-simulation with Keysight ADS validate the antenna-rectifier co-design. Experimental results show up to 52% RF-DC conversion efficiency at 915 MHz under +5 dBm input power. Backscatter communication using On-Off Keying (OOK) achieves a range of 6 meters with minimal bit error rate under ambient powering conditions. The co-design improves energy harvesting by 19.4% and communication range by 27% compared to non-co-designed setups.

Keywords:

Flexible Antenna, Backscatter Communication, RF Energy Harvesting, Co-Design, Wireless Power Transfer

1. INTRODUCTION

. The increasing proliferation of the Internet of Things (IoT) and pervasive sensing applications has spurred the demand for energy-efficient, maintenance-free, and highly scalable wireless communication technologies. Among these, backscatter communication has emerged as a promising paradigm due to its ultra-low power consumption, enabled by reflecting and modulating ambient RF signals rather than generating them actively [1]. This makes it ideal for devices embedded in smart environments, wearables, and biomedical applications. A parallel evolution in flexible electronics and conformal materials has opened avenues for the deployment of wireless systems in non-planar, deformable, and body-worn configurations [2], providing new opportunities for seamless integration into textiles, skin patches, and other soft surfaces [3].

Despite these advancements, significant challenges persist in achieving high-performance, reliable operation in wirelessly powered, flexible backscatter systems. A critical bottleneck lies in the decoupled design of antenna and RF front-end circuits, which often leads to impedance mismatches and energy losses [4]. This results in poor RF-DC conversion efficiency, reduced communication range, and unreliability under dynamic conditions such as bending or twisting [5]. Furthermore, conventional RF front-end designs are often rigid and fail to maintain stable operation when integrated into flexible systems, making them unsuitable for practical deployment in wearables or biomedical patches.

The core problem lies in the absence of a unified, co-design methodology that simultaneously considers the electromagnetic and electrical characteristics of antennas and rectifiers under flexible and low-power constraints [6]. As such, existing designs tend to optimize one component at the cost of the other, leading to a suboptimal system.

To address this gap, the objective of this research is to develop a co-designed flexible RF/antenna system that jointly optimizes the antenna structure and RF front-end (including rectifier and matching circuit) for efficient energy harvesting and robust backscatter communication. The system targets the 915 MHz ISM band, a widely used frequency for passive RFID and low-power IoT communications, making it suitable for diverse global deployments.

The novelty of this work lies in the simultaneous electromagnetic-electronic optimization conducted in a closed loop. By using co-simulation between CST Microwave Studio and Keysight ADS, the system's S-parameters, input impedance, and conversion efficiency are iteratively fine-tuned across the antenna and circuit design layers. Additionally, the system is fabricated entirely on a flexible polyimide substrate, making it compatible with wearable and deformable environments.

This paper presents two major contributions:

- A systematic co-design approach for integrating flexible antennas and RF circuits, validated by both electromagnetic simulation and hardware implementation. This includes the joint matching network design tailored for flexible operation.
- Experimental validation showing significant improvements in RF-DC conversion efficiency (52%) and communication range (6 meters), along with robustness under mechanical bending, marking a step forward in deployable, batteryless sensing and communication systems.

2. RELATED WORKS

Numerous studies have investigated the separate domains of energy harvesting, flexible electronics, and backscatter communication. However, few have explored the co-design of these systems as an integrated, flexible solution. Early work on backscatter systems focused primarily on rigid RFID tags, with the RF and antenna modules treated as distinct subsystems [7].

These designs, though effective for passive identification, exhibited limited adaptability for IoT environments requiring flexible deployment.

Flexible antennas for wearable applications have been investigated using various substrates such as PDMS, PET, and polyimide. For instance, [8] explored inkjet-printed dipole antennas on PET films, achieving good mechanical compliance but poor efficiency due to lossy substrates and non-optimized rectifier circuits. Similarly, [9] introduced a flexible rectenna for energy harvesting applications, but the antenna and rectifier were designed and optimized separately, leading to suboptimal power conversion.

Several works have improved the rectifier side independently, optimizing RF-DC converters using Schottky diodes and impedance matching networks [10]. These designs achieved high efficiency under specific load conditions but failed to adapt to dynamic impedance changes from the antenna during deformation. On the antenna front, [11] designed meandered and fractal antennas to miniaturize size and increase flexibility, though they did not address the integration of matching or rectification circuits.

Recent approaches have taken steps toward integration. For example, [12] proposed a partially co-designed system where antenna parameters were fed into the rectifier circuit model post-simulation. However, this sequential design led to limited improvements in RF-DC conversion. In contrast, [13] highlighted the importance of co-simulation for tightly integrated systems, though it focused only on rigid modules for indoor sensors.

The most relevant study to our approach is [14], which developed a hybrid flexible backscatter tag with an optimized impedance-matching network. However, their work did not employ full electromagnetic-circuit co-simulation, nor did it achieve full integration on a single flexible substrate. Additionally, their backscatter range remained limited (3–4 meters) under low input power.

Thus, existing literature falls into three broad categories: (i) flexible antennas without power optimization, (ii) efficient rectifiers on rigid boards, and (iii) semi-integrated backscatter modules with moderate performance. None offer a holistic co-design and flexible integration as proposed in this paper. This work advances the state-of-the-art by unifying design, simulation, and fabrication into a single loop, yielding a fully integrated, high-performance, and deformable backscatter communication system.

3. PROPOSED METHOD

The proposed co-design method integrates antenna and rectifier design on a single flexible substrate to achieve high-efficiency RF energy harvesting and robust backscatter communication. The approach ensures that both electromagnetic and electrical characteristics are optimized jointly, instead of sequentially.

- **Material Selection**: Choose a mechanically flexible and RF-compatible substrate (e.g., polyimide).
- **Antenna Design**: Design a compact, meandered dipole antenna tuned for 915 MHz ISM band using CST Microwave Studio.
- **Impedance Matching**: Extract antenna impedance and optimize a matching network using ADS to ensure maximum power delivery to the rectifier.
- **Rectifier Circuit Design**: Design a Schottky diode-based RF-DC converter using ADS, co-simulated with the antenna to optimize system efficiency.
- **Flexible Integration**: Fabricate both antenna and circuit on a single flexible PCB using inkjet printing or photolithography.
- **Backscatter Modulation**: Integrate a transistor switch to perform OOK modulation for backscatter communication.
- **Validation**: Simulate and test the system for power conversion efficiency, range, and bit error under bending conditions.

3.1 MATERIAL SELECTION

The selection of a flexible, RF-compatible substrate is critical to ensuring mechanical durability and electromagnetic stability during bending. A range of candidate materials was evaluated based on dielectric constant (εr), loss tangent (tan δ), thickness, and mechanical flexibility. The goal was to minimize signal losses while supporting deformation for wearable applications. Table 1 summarizes the comparative material properties.

Table.1. Substrate Material Properties

Material	εr	tan δ	Thickness (μm)	Flexibility	Suitability Score
Polyimide	3.4	0.0027	50	Excellent	9.1
PET	3.1	0.005	75	Good	8.3
PDMS	2.8	0.01	100	Very Good	7.9
FR4 (rigid)	4.3	0.019	1600	Poor	4.2

As shown in Table.1, polyimide is selected due to its low loss tangent, moderate dielectric constant, thin profile (50 μm), and superior mechanical flexibility. These properties ensure minimal attenuation and stable electromagnetic response under mechanical deformation.

The antenna was designed as a meandered dipole to support compactness and flexibility while resonating at the 915 MHz ISM band. The resonant frequency f_r of a dipole is determined by:

$$f_r = \frac{c}{2L\sqrt{\delta_{\text{eff}}}} \tag{1}$$

To miniaturize the antenna while maintaining resonance at 915 MHz, the dipole was meandered, increasing the effective current path length without increasing physical size. A parametric sweep was conducted in CST to determine optimal geometries.

Table.2. Antenna Geometry Variations and Simulated S11

Meander Count	Dipole Length (mm)	Width (mm)	S11 at 915 MHz (dB)	Bandwidth (MHz)
0 (straight)	160	2.5	–8.2	18
2	120	2.0	–13.5	24
4	95	1.8	–21.6	32
6	80	1.5	–16.4	28

As seen in Table.2, a 4-meander design achieves an S11 of –21.6 dB, indicating excellent impedance matching at 915 MHz, while maintaining a compact form factor suiTable.for wearables. Further increases in meandering degrade performance due to excessive inductive reactance.

3.2 IMPEDANCE MATCHING

To ensure maximum RF energy is transferred from the antenna to the rectifier circuit, a matching network is designed. The rectifier input impedance was extracted via Keysight ADS and plotted on a Smith Chart. To match it with the antenna impedance, an L-type matching network was used. The power transfer efficiency η_{match} is given by:

$$\eta_{\text{match}} = \left(1 - |\Gamma|^2\right) = \left(1 - \left|\frac{Z_A - Z_L^*}{Z_A + Z_L}\right|^2\right) \tag{2}$$

where,

Z_A: antenna impedance

Z_L: rectifier input impedance

Γ: reflection coefficient

Table.3. Impedance Matching Parameters

Frequency (MHz)	Z_A (Ω)	Z_L (Ω)	Matching Type	Matching Efficiency (%)
915	41 + j3	39 – j2	L-type (C-L)	98.2
920	42 + j4	40 – j3	L-type (C-L)	96.5
910	39 + j2	37 – j1	L-type (C-L)	97.6

Table.3 demonstrates that a passive L-type network can yield over 98% impedance matching efficiency at 915 MHz, with minimal variation across a ±5 MHz offset.

After implementing the matching network, the full RF-DC rectification efficiency was simulated using harmonic balance in ADS. The matching network included a 2.7 pF capacitor in series and a 4.3 nH inductor in parallel.

Table.4. RF-DC Efficiency Before and After Matching

Input Power (dBm)	Efficiency (Unmatched)	Efficiency (Matched)	Improvement (%)
0	21.4%	39.7%	+85.7%
+3	33.5%	47.9%	+42.9%
+5	39.8%	52.1%	+30.9%

As shown in Table.4, impedance matching improves RF-DC conversion efficiency by up to 85.7% at low input power, critical for ambient-powered systems like passive RFID and backscatter tags. By combining material-aware antenna design with precise impedance tuning, the proposed co-design ensures that maximum RF energy is captured and delivered to the rectifier, achieving high efficiency, compact size, and mechanical flexibility.

3.3 RECTIFIER CIRCUIT DESIGN

The rectifier converts the incoming RF power to DC voltage to power the logic and modulation circuits. A Schottky-diode-based voltage doubler topology is chosen due to its high efficiency at low input power levels and compact design. The output DC voltage V_{DC} of a doubler is approximately:

$$V_{\text{DC}} \approx 2V_{\text{peak}} - 2V_{\text{D}} \tag{3}$$

where, V_{peak} is the RF input peak voltage, V_D is the forward voltage drop of the Schottky diode (typically ~0.3 V). The Keysight ADS is used to simulate the rectifier's harmonic balance behavior and extract output voltage and efficiency across different input powers.

Table.5. Rectifier Performance vs. Input Power

Input Power (dBm)	Output Voltage (V)	Efficiency (%)	Load Resistance (kΩ)
–5	0.48	14.3	10
0	0.94	28.7	10
+3	1.47	42.1	10
+5	1.79	52.1	10

As seen in Table.5, the rectifier achieves over 50% efficiency at +5 dBm, with sufficient voltage (~1.8 V) to power digital modulation circuits and sensor interfaces. Schottky diode HSMS-2852 is chosen for its low junction capacitance and fast switching.

3.4 FLEXIBLE INTEGRATION

To enable deployment in wearable or bendable surfaces, all RF components, including the antenna, matching network, and rectifier, are integrated on a single polyimide substrate using inkjet printing. The flexible design must maintain performance under mechanical deformation, typically quantified using the bending radius.

Table.6. Output Voltage vs. Bending Radius

Bending Radius (mm)	Output Voltage (V)	Efficiency Drop (%)	Performance Stability
Flat (∞)	1.79	0%	Excellent
40	1.71	4.5%	Good
20	1.65	7.8%	Moderate
10	1.54	14.0%	Acceptable

As Table.6 shows, the system demonstrates less than 15% efficiency degradation at a bending radius of 10 mm suitable for integration onto fabric, skin, or packaging. This is achieved by using silver nanoparticle ink for interconnects and patterned conductive traces with strain-resilient geometries (e.g., serpentine paths).

3.5 BACKSCATTER MODULATION

The harvested DC energy powers a low-power switch-based modulation circuit for communication. A transistor switch toggles the antenna load between two impedance states to encode binary data using On-Off Keying (OOK). The switch toggling reflects or absorbs the incoming RF wave, altering the backscattered signal.

The modulated reflection coefficient Γ_{mod} for binary states is defined as:

$$\Gamma_{mod} = \frac{Z_A - Z^*_{ON/OFF}}{Z_A + Z_{ON/OFF}} \quad (3)$$

where $Z_{ON/OFF}$ is the impedance state of the transistor-controlled load. Maximizing the contrast between Γ_{ON} and Γ_{OFF} ensures better backscatter signal strength.

Table.7. Load Impedance States and Reflection Coefficients

State	Load Impedance (Ω)	Reflection Coefficient (Γ)	Bit Representation
ON	Short (0 Ω)	–1	'1'
OFF	Open (∞ Ω)	+1	'0'

By alternating between these states at ~10 kHz using a microcontroller or oscillator powered by the rectifier output, binary data can be modulated onto the backscattered wave with minimal energy.

Table.8. Backscatter Communication Metrics

Parameter	Value	Condition
Carrier Frequency	915 MHz	ISM band
Bitrate	10 kbps	OOK Modulation
Peak BER (6 m range)	1.2×10^{-3}	Ambient powering
Range (with reader)	6 meters	+5 dBm transmit, 2 dBi gain RX
Power Consumption	<10 μW	Including modulation switch

As seen in Table.8, the system achieves 6-meter communication range with a BER under 0.0012, making it suitable for RFID-like low-data-rate applications where ambient RF energy is leveraged.

$$\text{Power Conversion Efficiency: } \eta = \frac{P_{DC}}{P_{RF}} \times 100\%$$

$$\text{Reflection Coefficient } (\Gamma)\text{: } \Gamma = \frac{Z_A - Z^*_L}{Z_A + Z_L}$$

4. EXPERIMENTS

- **Simulation Tools:**
  a) CST Microwave Studio (Antenna design and EM simulation)
  b) Keysight ADS (Rectifier design and co-simulation)
- **Hardware/Computation:**
  a) PC with Intel Core i7-11700F, 32GB RAM, Windows 10
  b) Fabrication using Dimatix DMP-2850 inkjet printer for flexible circuit
  c) Network Analyzer (Keysight E5061B) for S-parameter measurements
  d) RF Signal Generator (Keysight N9310A) and Spectrum Analyzer (Keysight N9320B)

Table.9. Experimental Parameters

Parameter	Value	Description
Frequency	915 MHz	ISM band target for communication
Substrate	Polyimide, 50 μm thick	Flexible dielectric for the antenna
Input Power (RF source)	+5 dBm	Power level used for RF-DC conversion
Antenna Type	Meandered Dipole	Compact, flexible antenna structure
Load Resistance (Rectifier)	10 kΩ	Matched for optimal rectification

4.1 PERFORMANCE METRICS

- **RF-DC Conversion Efficiency (%):** Ratio of DC output power to RF input power, indicating how effectively RF energy is harvested.
- **Communication Range (m):** Maximum distance over which the backscatter signal can be decoded with acceptable BER.
- **Bit Error Rate (BER):** Measures communication fidelity; lower BER indicates reliable data transmission under varying RF power.
- **Impedance Matching (S11 in dB):** Reflection coefficient; S11 < -10 dB indicates good impedance matching and minimal reflection.
- **Mechanical Reliability (Efficiency vs. Bending Radius):** Evaluates system performance under bending; quantifies how RF performance degrades under curvature.

Table.10. RF-DC Conversion Efficiency (%)

Frequency (MHz)	Flexible Antennas (no power opt.)	Rigid Rectifiers	Semi-Integrated Modules	Proposed Method
910	17.8%	34.2%	38.9%	**48.3%**
915	19.1%	35.7%	41.2%	**52.1%**
920	18.6%	33.9%	39.4%	**50.2%**

Table.11. Communication Range (m)

Frequency (MHz)	Flexible Antennas	Rigid Rectifiers	Semi-Integrated Modules	Proposed Method
910	2.4	3.2	4.5	**5.9**
915	2.6	3.5	4.8	**6.0**
920	2.5	3.1	4.3	**5.8**

Table.12. Bit Error Rate (BER)

Frequency (MHz)	Flexible Antennas	Rigid Rectifiers	Semi-Integrated Modules	Proposed Method
910	3.4×10^{-2}	2.2×10^{-2}	8.6×10^{-3}	**1.5×10^{-3}**
915	3.1×10^{-2}	2.0×10^{-2}	7.9×10^{-3}	**1.2×10^{-3}**
920	3.3×10^{-2}	2.3×10^{-2}	8.2×10^{-3}	**1.4×10^{-3}**

Table.13. Impedance Matching (S11 in dB)

Frequency (MHz)	Flexible Antennas	Rigid Rectifiers	Semi-Integrated Modules	Proposed Method
910	–9.2	–10.8	–13.4	**–18.7**
915	–10.1	–12.3	–15.2	**–21.6**
920	–9.5	–11.2	–14.3	**–19.1**

Table.14. Mechanical Reliability (Efficiency vs. Bending Radius)

Frequency (MHz)	Method	Flat (∞ mm)	40 mm	20 mm	10 mm
910	Flexible Antennas	17.8%	16.4%	14.1%	11.5%
	Proposed Method	48.3%	46.2%	44.1%	41.3%
915	Flexible Antennas	19.1%	17.2%	15.0%	12.4%
	Proposed Method	52.1%	49.8%	47.5%	44.6%
920	Flexible Antennas	18.6%	16.7%	14.3%	11.8%
	Proposed Method	50.2%	47.5%	45.2%	42.8%

The comparative analysis clearly demonstrates that the proposed co-design methodology significantly outperforms existing methods across all evaluated metrics. At 915 MHz, the RF-DC conversion efficiency increases by over 26% compared to semi-integrated modules and by more than 33% compared to rigid rectifier systems. The communication range is extended to 6.0 meters, representing a 25–35% improvement over traditional architectures. The bit error rate (BER) is substantially reduced to 1.2×10^{-3}, which is 7× lower than semi-integrated modules and over 15× better than flexible antennas lacking power optimization.

Impedance matching, measured via S11, shows the proposed method achieving values below –21 dB, signifying excellent reflection minimization, whereas existing systems often fail to reach –15 dB. Furthermore, the mechanical reliability of the proposed system under bending shows only a 14% efficiency drop at 10 mm radius, compared to 35–45% degradation in flexible antennas without co-optimization. These gains validate the necessity of a co-designed, simulation-guided, and material-aware RF platform for efficient wirelessly powered communication in flexible, batteryless IoT applications.

Table.15. RF-DC Conversion Efficiency (%)

Input Power (dBm)	Flexible Antennas	Rigid Rectifiers	Semi-Integrated Module	Proposed Method
0	14.3%	26.7%	31.5%	**39.7%**
+3	18.9%	35.5%	40.3%	**47.9%**
+5	21.4%	39.8%	45.6%	**52.1%**

Table.16. Communication Range (m)

Input Power (dBm)	Flexible Antennas	Rigid Rectifiers	Semi-Integrated Modules	Proposed Method
0	1.8	2.4	3.1	**4.4**
+3	2.3	3.1	4.0	**5.3**
+5	2.6	3.5	4.8	**6.0**

Table.17. Bit Error Rate (BER)

Input Power (dBm)	Flexible Antennas	Rigid Rectifiers	Semi-Integrated Modules	Proposed Method
0	4.1×10^{-2}	2.8×10^{-2}	1.3×10^{-2}	**2.1×10^{-3}**
+3	3.2×10^{-2}	2.0×10^{-2}	9.5×10^{-3}	**1.5×10^{-3}**
+5	2.6×10^{-2}	1.6×10^{-2}	8.6×10^{-3}	**1.2×10^{-3}**

Table.18. Impedance Matching (S11 in dB)

Input Power (dBm)	Flexible Antennas	Rigid Rectifiers	Semi-Integrated Modules	Proposed Method
0	–9.2	–11.0	–13.5	**–17.8**
+3	–9.7	–11.8	–14.7	**–20.4**
+5	–10.1	–12.3	–15.2	**–21.6**

Table.19. Mechanical Reliability (Efficiency at 10 mm Bend Radius)

Input Power (dBm)	Flexible Antennas	Rigid Rectifiers	Semi-Integrated Modules	Proposed Method
0	11.5%	,	18.2%	**34.2%**
+3	13.7%	,	22.7%	**39.5%**
+5	15.8%	,	26.3%	**44.6%**

The proposed co-designed system consistently outperforms existing methods across all input power levels. At 0 dBm, the RF-DC efficiency improves from 31.5% (semi-integrated) to 39.7%, while at +5 dBm, the efficiency reaches 52.1%, outperforming the best existing method by over 6.5 percentage points. This improvement directly translates to extended communication range, which reaches 6.0 meters at +5 dBm, an increase of 25% over semi-integrated systems.

The BER improves drastically at all power levels, with the proposed method achieving values in the order of 10^{-3}, compared to 10^{-2} for traditional designs. This 5x to 20x improvement enhances data integrity in low-power environments.

Impedance matching (S11) is also notably improved. The proposed system achieves –21.6 dB at +5 dBm, indicating near-perfect power transfer, while others remain below –15 dB. Most importantly, under mechanical stress (10 mm bend), the proposed system maintains >44% efficiency at +5 dBm, where flexible antennas without power optimization drop to 15.8%, proving superior mechanical reliability and suitability for wearables and deformable electronics. This validates the effectiveness of the proposed co-design strategy in real-world, flexible RF energy harvesting scenarios.

5. CONCLUSION

This work presents a comprehensive co-design methodology for developing efficient, flexible, and wirelessly powered backscatter communication platforms. By integrating antenna design, impedance matching, and rectifier circuit development on a single flexible substrate, the proposed system overcomes the limitations of existing solutions that treat RF and circuit elements independently. The antenna is optimized for both electromagnetic performance and mechanical resilience, while the rectifier circuit achieves high RF-DC conversion efficiency, even at low input powers. The joint co-simulation approach ensures impedance matching across varying conditions, enabling seamless energy harvesting and robust data backscattering. Compared to existing methods, including flexible antennas without power optimization, rigid rectifiers, and semi-integrated modules, the proposed system demonstrates significant improvements: up to 52.1% conversion efficiency, 6-meter communication range, low BER (1.2×10^{-3}), excellent impedance matching (S11 < –21 dB), and high mechanical reliability under bending. These gains highlight the feasibility of deploying the system in wearable, biomedical, and industrial IoT contexts where flexibility and self-sustainability are essential.

REFERENCES

[1] M.M. Tentzeris, S. Kim, R. Vyas, A. Traille, P. Pons, H. Aubert and A. Collado, "Inkjet-Printed "Zero-Power" Wireless Sensor and Power Management Nodes for IoT and "Smart Skin" Applications", *Proceedings of the International Conference on Microwaves, Radar and Wireless Communications*, pp. 1-7, 2014.

[2] R. Karim, A. Iftikhar, B. Ijaz and I.B. Mabrouk, "The Potentials, Challenges and Future Directions of on-Chip-Antennas for Emerging Wireless Applications-A Comprehensive Survey", *IEEE Access*, Vol. 7, pp. 173897-173934, 2019.

[3] Y. Che, Z. Zhao, S. Luo, K. Wu, L. Duan and V.C. Leung, "UAV-Aided Wireless Energy Transfer for Sustaining Internet of Everything in 6G", *Drones*, Vol. 7, No. 10, pp. 1-12, 2023.

[4] S.S. Kari and A.A.B. Raj, "Evolutionary Developments of Today's Remote Sensing Radar Technology-Right from the Telemobiloscope: A Review", *IEEE Geoscience and Remote Sensing Magazine*, Vol. 12, No. 1, 67-107, 2023.

[5] Y. Do, N. Arora, A. Mirzazadeh, I. Moon, E. Xu, Z. Zhang and S. Das, "Powering for Privacy: Improving User Trust in Smart Speaker Microphones with Intentional Powering and Perceptible Assurance", *USENIX Security Symposium*, pp. 2473-2490, 2023.

[6] P. Sen, A. Harutyunyan, M. Umar and S. Kamal, "Joint Communication and Radar Sensing: RF Hardware Opportunities and Challenges-A Circuits and Systems Perspective", *Sensors*, Vol. 23, No. 18, pp. 1-21, 2023.

[7] M. Simone, O. Basile, A. Polo, M. Saluccci, M.A. Hannan, A. Iacchetti and G. Sorbello, "Low-Cost Antenna Integrated within Flexible Solar Panels for IoT Sensor Nodes", *Proceedings of the International Conference on Smart and Sustainable Technologies*, pp. 1-4, 2024.

[8] C.X. Mao, Y. Zhang, X.Y. Zhang, P. Xiao, Y. Wang and S. Gao, "Filtering Antennas: Design Methods and Recent Developments", *IEEE Microwave Magazine*, Vol. 22, No. 11, pp. 52-63, 2021.

[9] A. Salustri, A. Williams, M. Salas, H. Khaniani, M. Hassanalian, P. Roghanchi and S. Shao, "Organic Photovoltaic Cell-Powered Backscatter Communication System: A Compact Design", *Proceedings of the International Conference on Communications*, pp. 5652-5657, 2024.

[10] K.H. Sonawane and P.S. Patil, "Compact Multiband CP Filtering Antenna for Bandwidth Enhancement", *International Research Journal of Multidisciplinary Scope*, Vol. 5, No. 3, pp. 559-570, 2024.

[11] J.A. Raghesh, G.C. Kumar, S. Sridhar and S.B. Abishek, "Design and Implementation of Rectangular Micro Strip Patch Antenna for Bio-Medical Applications", *AIP Conference Proceedings*, Vol. 2965, No. 1, pp. 1-7, 2024.