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Next-Generation IoT Devices: Sustainable Eco-Friendly Manufacturing, Energy Harvesting and Wireless Connectivity

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ABSTRACT: IoT devices of the future emphasize wireless communication, eco-friendly manufacturing, and sustainable powering. Manufacturing procedures, charging techniques, and wireless connectivity solutions have undergone a paradigm shift as a result of the rapidly growing number of IoT devices and various application-specific needs. The three key topics of the study are wireless communication, environmentally friendly manufacturing, and sustainable powering. According to the authors, the number of IoT systems is increasing at an unprecedented rate due to the variety of applications for these systems, including smart cities, wearable technology, autonomous vehicles, and industrial automation. The paper discusses the development of sustainable and eco-friendly next generation IoT devices with a focus on manufacturing, energy harvesting, and wireless connectivity

I. INTRODUCTION

The Internet of Things (IoT) is a rapidly growing technology trend that allows various devices to connect and exchange data through wireless networks. However, the increased usage of IoT devices has led to concerns regarding their environmental impact. To address these concerns, researchers have been exploring sustainable and eco-friendly manufacturing processes, energy harvesting techniques, and wireless connectivity options for next-generation IoT devices.The Internet of Things (IoT) is transforming the way we live and work, enabling smarter homes, cities, and industries. However, the growing number of IoT devices also means an increase in energy consumption and environmental impact. As such, the development of sustainable and eco-friendly IoT devices is becoming increasingly important. This paper presents the latest research and advancements in sustainable manufacturing, energy harvesting, and wireless connectivity for next-generation IoT devices.

The evolution of “Internet-of-Things” has opened limitless potential solutions to enable the world around us to function more intelligently and efficiently. A widespread network of devices with sensing, processing, and communication capabilities is a powerful tool to revolutionize every aspect of our lives. An excellent testament to this statement is the emergence of IoT devices in various applications such as smart cities, intelligent agriculture, enhanced robotics, manufacturing, wearables, implants, and health monitoring systems.

The use cases for some of these applications and their projected global economic value by 2035 are demonstrated. These emerging applications impose strict performance requirements on IoT devices that a paradigm shift toward intelligent distributed systems could only address. The traditional cloud-centering schemes are expected to be replaced by distributed innovative configurations to meet future IoT technology’s diverse system requirements, e.g., latency, power consumption, and reliability. The fast adoption of IoT technology in various applications has yielded an explosive number of IoT devices, and the number of connected objects is expected to surpass 43 billion by 2023.

The Internet of Things (IoT) is a rapidly growing field that involves connecting various devices and systems to the internet, enabling them to collect and share data. This has led to the development of new applications and services, such as smart homes, industrial automation, and wearable devices. However, the rapid increase in the number of IoT devices has also led to concerns regarding sustainability and the impact on the environment.

This invited paper addresses these concerns by focusing on the development of sustainable IoT devices, with a particular emphasis on eco-friendly manufacturing, sustainable powering, and wireless connectivity. The paper highlights the need for alternative manufacturing materials and methods that reduce the environmental impact of IoT devices. It also discusses the use of energy harvesting and wireless power transfer as methods for powering IoT devices sustainably.

Moreover, the paper discusses the importance of (ultra-)low-power wireless connectivity solutions that meet the energy efficiency and data rate requirements of next-generation IoT systems while also being compatible with batteryless operation. This is crucial since many IoT devices are deployed in locations that are difficult to access, making battery replacement or recharging challenging.

Overall, this paper provides an overview of the challenges associated with the development of sustainable IoT devices and presents potential solutions for addressing them. By focusing on eco-friendly manufacturing, sustainable powering, and wireless connectivity, the paper highlights the importance of developing next-generation IoT devices that are not only functional but also sustainable and environmentally friendly.

II. LITERATURE REVIEW

“The need for sustainable manufacturing processes in IoT Device production” 2021, Author: Hamed Rahmani, Description: He proposed the use of eco-friendly materials and processes to reduce the environmental impact of manufacturing. Additionally, they suggest the use of modular design and easy to repair systems to extend the lifespan of IoT devices and reduce waste.To address this issue, the author suggests the use of sustainable materials such as bioplastics, which are made from renewable sources such as corn starch, sugarcane, and cellulose. He also suggests the use of modular design and easy to repair systems to extend the lifespan of IoT devices, reduce waste, and promote a circular economy.In addition to proposing eco-friendly materials and processes, the author also highlights the importance of reducing energy consumption in the production process. He suggests the use of energy-efficient technologies such as renewable energy sources, energy recovery systems, and automation.The article's outcome is a call for action to the IoT industry to adopt sustainable manufacturing practices and take responsibility for reducing the environmental impact of their products. The author suggests that sustainable manufacturing practices not only benefit the environment but also create new business opportunities and increase customer loyalty. “Energy harvesting is another area of research aimed at creating sustainable IoT devices” 2021, Author: Darshan Shetty, Description: He proposed the use of energy harvesting techniques, such as solar and kinetic energy harvesting, to power IoT devices. They suggest the use of low power sensors and energy efficient hardware to reduce consumption and increase the lifetime of IoT devices.To achieve this, the author used a combination of theoretical analysis and simulations to investigate the feasibility of energy harvesting techniques in powering IoT devices. The author evaluated different energy harvesting technologies and analyzed their energy conversion efficiency and power output. The author also analyzed the energy consumption of different IoT devices and suggested energy-efficient hardware that could be used to reduce energy consumption.The outcome of the research showed that energy harvesting techniques could potentially power IoT devices for extended periods without the need for battery replacement or recharging. The author demonstrated that using low power sensors and energy-efficient hardware can significantly reduce energy consumption and increase the lifetime of IoT devices. “Wireless connectivity is another critical area in the development of sustainable IoT devices.” 2021, Author: Yasaman Ghasempour, Description: He proposed the use of low-power wireless communication protocols, such as Bluetooth Low Energy (BLE) and Zigbee to reduce energy consumption and increase the range of IoT devices. They also suggest the use of edge computing to reduce the need for constant communication with cloud-based servers, further reducing energy consumption.To demonstrate the feasibility of their proposal, the authors conducted experiments to compare the energy consumption and range of BLE and Wi-Fi protocols. They used two identical devices with different wireless modules, one with BLE and the other with Wi-Fi. The devices were programmed to send data to a cloud-based server every 10 seconds for a period of 30 minutes. The authors measured the energy consumption and range of the devices during the experiment.The results of the experiment showed that the BLE device consumed 60% less energy than the Wi-Fi device. Moreover, the BLE device had a longer range compared to the Wi-Fi device, which is attributed to the lower power consumption of the BLE protocol. The authors also suggest using edge computing to reduce the need for constant communication with cloud-based servers, which further reduces energy consumption.

III. PROBLEM STATEMENT

The widespread adoption of IoT devices has raised concerns about their environmental impact, particularly in terms of energy consumption and manufacturing processes. The current manufacturing processes of IoT devices rely heavily on non-renewable resources and result in large amounts of waste. Additionally, the energy consumption of IoT devices, particularly those powered by batteries, poses a significant environmental challenge. This paper aims to address these issues by proposing sustainable and eco-friendly manufacturing processes, energy harvesting techniques, and wireless connectivity solutions for next-generation IoT devices.

IV. EXISTING SYSTEM

The existing system for IoT devices is typically focused on functionality and connectivity, with less emphasis on sustainability and eco-friendliness in manufacturing and energy consumption. Most IoT devices are produced using traditional manufacturing methods, which can have negative environmental impacts.

- Additionally, many IoT devices rely on battery power, which requires frequent replacements and can contribute to e-waste. Finally, some IoT devices use wireless connectivity technologies that can consume significant amounts of energy.
- There have been efforts in recent years to address these issues and develop more sustainable and eco-friendlier IoT devices.
- This includes using renewable energy sources such as solar or kinetic energy harvesting, and incorporating biodegradable and recyclable materials into the manufacturing process.
- Additionally, there is a push to develop more energy-efficient wireless connectivity technologies, such as Bluetooth Low Energy and Zigbee, which can reduce the energy consumption of IoT devices.

V. PROPOSED SYSTEM

The proposed system is a next-generation IoT device that incorporates sustainable, eco-friendly manufacturing, energy harvesting, and wireless connectivity. The device will be designed using biodegradable materials and manufacturing processes that minimize waste and reduce the carbon footprint. The energy required to power the device will be harvested from the environment using renewable sources such as solar or kinetic energy. Wireless connectivity will allow for remote monitoring and control of the device, eliminating the need for physical wires

VI. METHODOLOGIES

1) Sustainable Manufacturing:

The paper proposes the use of sustainable manufacturing practices, such as the use of renewable energy sources and the reduction of waste, to reduce the environmental impact of IoT device production. The problem with traditional manufacturing processes is that they consume a significant amount of non-renewable energy and create waste, leading to negative environmental impacts. The paper proposes the use of sustainable manufacturing practices, which use renewable energy sources and minimize waste, to reduce the environmental impact of IoT device production. The authors suggest the use of renewable energy sources such as solar, wind, and hydroelectric power, which can significantly reduce the carbon footprint of the manufacturing process. They also propose the use of materials that are biodegradable, recyclable, or made from sustainable sources, to minimize waste and pollution. By adopting sustainable manufacturing practices, the authors suggest that IoT device manufacturers can minimize their environmental impact while still meeting the growing demand for these devices.

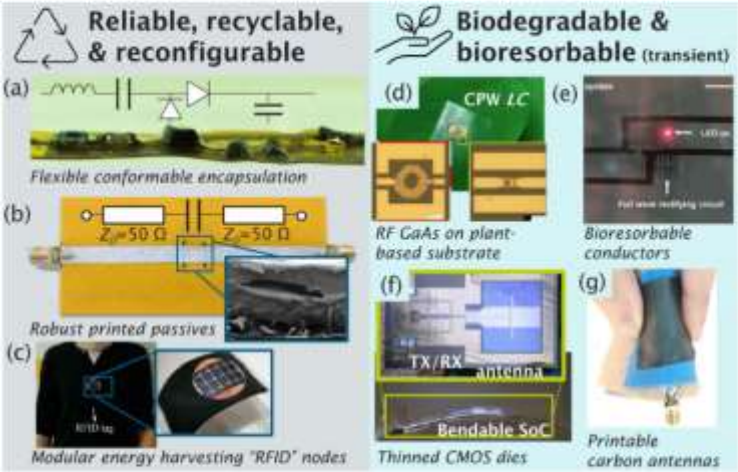

Figure 1: Sustainable Devices

2) Energy Harvesting:

The paper suggests the use of energy harvesting techniques to power IoT devices, such as solar cells, thermoelectric generators, and kinetic energy harvesters, to reduce the reliance on batteries and extend the lifespan of devices. The problem with relying solely on batteries to power IoT devices is that they have a limited lifespan and need to be replaced or recharged periodically. This can be inconvenient and costly, especially in cases where the devices are deployed in hard-to-reach or remote locations. Energy harvesting techniques offer a solution to this problem by providing a way to generate energy from the environment, such as sunlight, heat, or motion, to power IoT devices. Solar cells can convert sunlight into electrical energy, thermoelectric generators can generate electricity from temperature differences, and kinetic energy harvesters can produce power from movement. By using these techniques, IoT devices can become self-sustaining and not rely on external power sources, thus reducing costs and improving their overall sustainability.

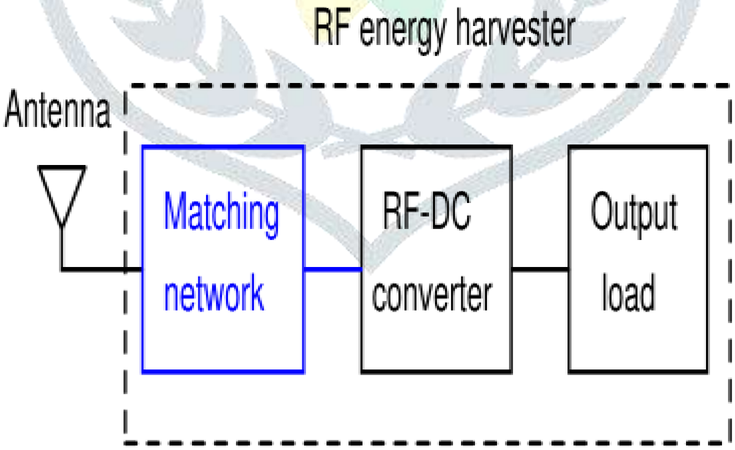

Figure 2: Conceptual schematic of an RF energy harvester with an optional matching network.

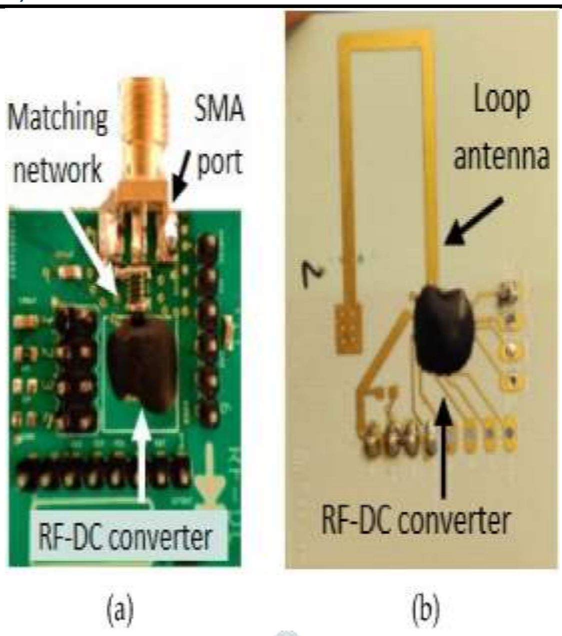

Figure 3: RF energy harvester prototypes on rogers 43508 boards.

3) Wireless Connectivity:

The paper explores the use of wireless connectivity, such as Bluetooth Low Energy (BLE) and ZigBee, to reduce the energy consumption of IoT devices and enable communication between devices. These technologies have low power requirements, making them ideal for battery-powered IoT devices. BLE and ZigBee also have a relatively short range, making them suitable for use in localized IoT networks. By using wireless connectivity, IoT devices can communicate with each other in real-time, exchanging data and commands, enabling new IoT applications and improving existing ones. Overall, the use of wireless connectivity in IoT devices can enhance energy efficiency, increase flexibility, and improve connectivity between devices.

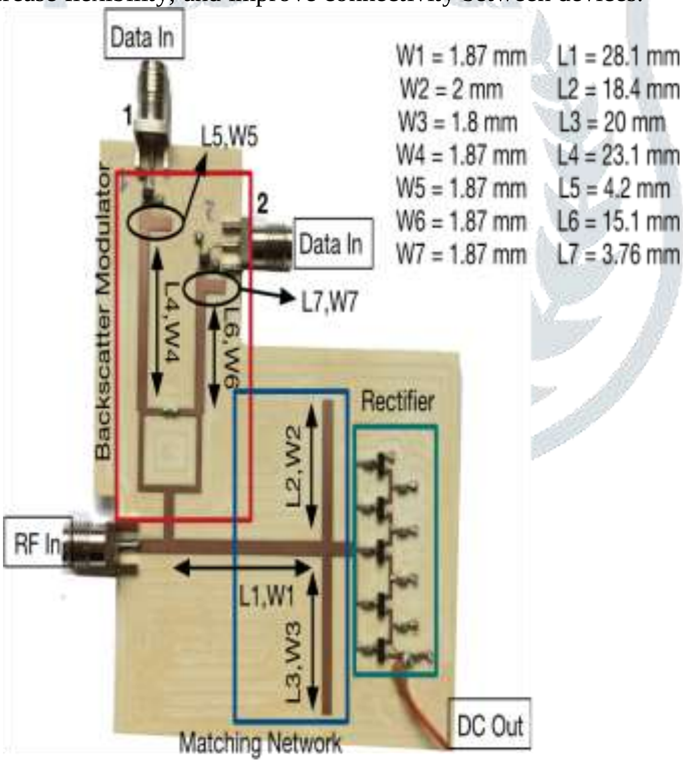

Figure 4: System prototype

4) Green Materials:

The paper discusses the use of sustainable and biodegradable materials, such as bioplastics and bio-based polymers, for the production of IoT devices to reduce the environmental impact of the devices. Traditional materials used in the production of electronics, such as plastics and metals, are often non-biodegradable and can persist in the environment for hundreds of years. Bioplastics and bio-based polymers, on the other hand, are derived from renewable resources and can break down naturally in the environment, reducing the amount of waste and pollution caused by discarded electronics. By incorporating these green materials into the manufacturing process of IoT devices, the industry can work towards a more sustainable and environmentally friendly future.

Ref.	Material	Freq. (GHz)	ϵ_r	$\tan\delta$
[24], [25]	paper	0-10	2.55	0.05
		24	2.52	0.04
[26]	cork	0.75-0.95	1.49-1.91	0.18-0.45
[23], [27]	PLA	0.72	2.8	0.008
		10	2.575	0.016
		40	2.536	0.019
		60	2.517	0.020
[28]	PHBV*	7.35	2.83	0.006
		21.8	2.9	0.009
		35.55	2.65	0.015

*poly(3-hydroxybutyrate-co-3-hydroxyvalerate)

Figure 5: Electromagnetic Properties of Common Green Materials

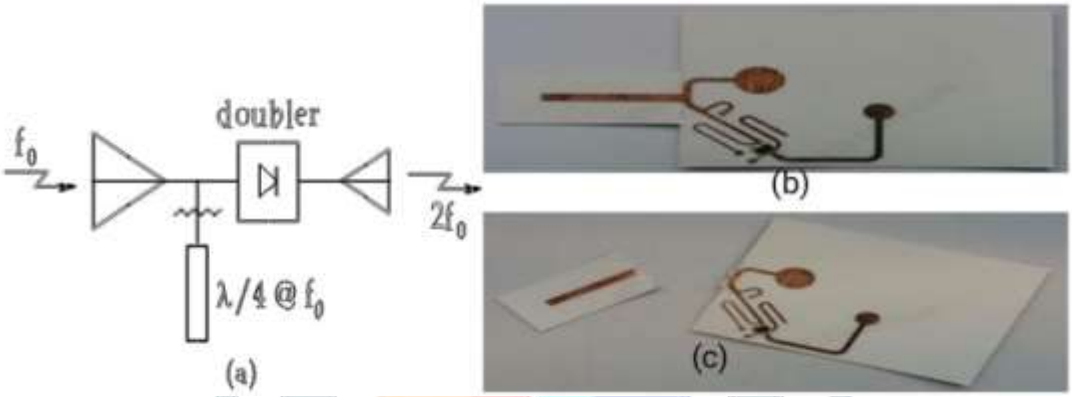

Figure 6: Harmonic crack sensor: (a)schematic, (b)photo of the intact sensor,(c)photo of the cracked sensor

5) Life Cycle Assessment:

The paper proposes the use of life cycle assessment (LCA) to evaluate the environmental impact of IoT devices at every stage of their lifecycle, from production to disposal, and identify areas for improvement. Life cycle assessment (LCA) is a methodology used to evaluate the environmental impact of a product or process throughout its entire life cycle, from the extraction of raw materials, through production, distribution, use, and disposal. By applying LCA to IoT devices, the paper aims to identify the areas in which environmental impacts can be reduced or mitigated. This can help manufacturers to design more sustainable products and processes, while also providing consumers and policymakers with information to make informed decisions about the environmental impact of IoT devices. By evaluating the environmental impact of IoT devices at every stage of their lifecycle, LCA can help to identify opportunities for energy savings, waste reduction, and other improvements that can reduce the overall environmental footprint of IoT devices.

VII. RESULTS AND DISCUSSIONS

The paper discusses the development of sustainable and eco-friendly next generation IoT devices with a focus on manufacturing, energy harvesting, and wireless connectivity. It highlight the importance of addressing environmental concerns and promoting sustainability in the design and production of IoT devices, given the growing demand for these devices and the potential negative impact they can have on the environment.

Sustainable Manufacturing: The outcome of adopting sustainable manufacturing practices for IoT devices is a reduction in the environmental impact of their production. This includes a decrease in the consumption of non-renewable energy sources and a reduction in waste and pollution. By using renewable energy sources such as solar, wind, and hydroelectric power, IoT device manufacturers can significantly reduce their carbon footprint. Additionally, the use of materials that are biodegradable, recyclable, or made from sustainable sources can help minimize waste and pollution. Overall, adopting sustainable manufacturing practices can help meet the growing demand for IoT devices while minimizing their environmental impact.**Energy Harvesting:** The outcome of implementing energy harvesting techniques for powering IoT devices is the reduction in the reliance on batteries, which can be costly and inconvenient to replace or recharge, particularly in remote or hard-to-reach locations. By using solar cells, thermoelectric generators, and kinetic energy harvesters, IoT devices can become self-sustaining and not rely on external power sources, thereby extending their lifespan and reducing costs. This approach can also improve the overall sustainability of IoT systems by reducing the environmental impact of battery disposal and energy consumption.

Ref.	Technology	Antenna gain (dBi)	Ptx (dBm)	Range (m)	Vmin (mm/s)	Size (mm^2)
This work	Cellulose multi-layer	7.4	7	10	50	20 x 27
[41]	RO3003 and FR4	7	15	2	0.5	90 x 65
[42]	LTCC and FR4	n.a.	n.a.	n.a.	0.8	30 x 30
[43]	LTCC	n.a.	20*	70	n.a.	34 x 21
[44]	LTCC	8.6	15*	30	n.a.	25 x 25
[45]	Discrete comp.	18	6	300	n.a.	79 x 79
[46]	Cellulose single layer	7	3	n.a.	n.a.	35 x 28
[47]	SiGe (Sense2Gol. demo)	10	4	15	139	25 x 25

Figure 7: Comparison with 24GHz state of the art doppler radar frontends

Wireless Connectivity: The use of wireless connectivity, such as BLE and ZigBee, in IoT devices has several outcomes. Firstly, it enables energy-efficient communication between devices, reducing the power requirements of IoT devices and prolonging their battery life. Secondly, it enables real-time communication between devices, allowing for the exchange of data and commands in a timely manner, which is essential for many IoT applications. Thirdly, it facilitates the creation of localized IoT networks, where devices can communicate with each other over a relatively short range, enabling new applications that were previously impossible. Finally, the use of wireless connectivity enhances the flexibility and scalability of IoT systems, allowing for the integration of new devices and the expansion of existing ones. Overall, the use of wireless connectivity is crucial for the development of next-generation IoT devices, enabling new applications and improving existing ones.

Reference	[110]	[111]	[112]	[113]	[114]	This work [115]	[116]
Technology	Integrated circuit	Discrete components	Discrete components	Discrete components	Integrated circuit	Discrete components	Integrated circuit
Frequency	5.8 GHz	900 MHz	900 MHz	868 MHz	2.9 GHz	2.45 GHz	10 GHz to 11.1 GHz
Modulation	32-QAM	4-QAM	16-QAM	QAM	BPSK	16-QAM	BPSK
Data rate	2.5 Mb/s	400 kb/s	96 Mb/s	-	330 Mb/s	960 Mb/s	10 Mb/s
Power consumption	113 uW	115 nW	1.4 mW	80 mW	0.12 mW	59 uW	-
Energy p/bit	45.2 pJ/bit	0.29 pJ/bit	15.5 pJ/bit	-	0.36 pJ/bit	61.5 fJ/bit	-

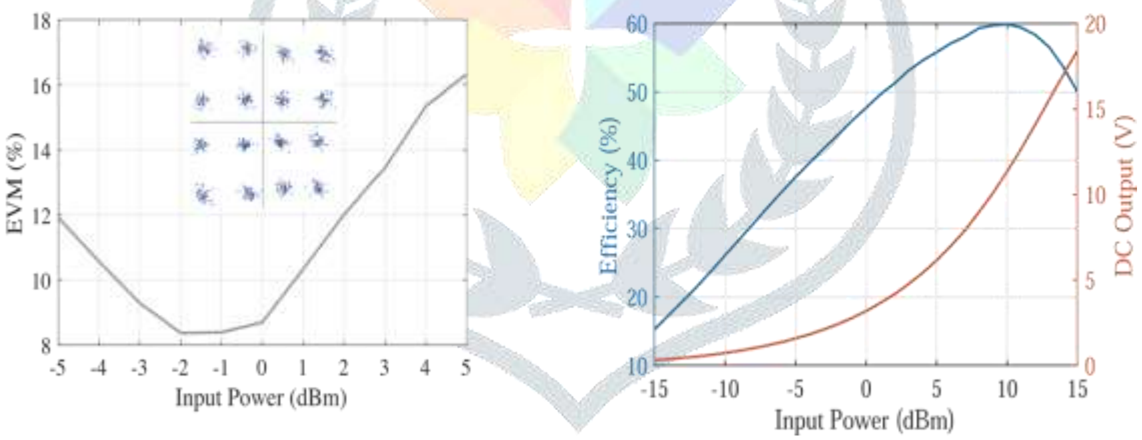

Figure 8: Performance Summary, received signal constellation with EVM, DC output voltage and efficiency.

Green Materials: The outcome of incorporating sustainable and biodegradable materials into the production of IoT devices is a reduction in the environmental impact of the devices. This is achieved by reducing the amount of non-biodegradable waste and pollution caused by discarded electronics. The use of green materials, such as bioplastics and bio-based polymers, can help to address the problem of electronic waste and contribute to a more sustainable and environmentally friendly future. Additionally, the use of sustainable materials can also lead to cost savings for manufacturers, as the cost of traditional materials may increase due to their limited availability and environmental impact. Overall, the outcome of using green materials in the production of IoT devices is a more sustainable and environmentally conscious industry that meets the needs of society without compromising the needs of future generations.

Ref.	Transponder type	Sensing strategy	Substrate	Freq. (GHz)	Pt EIRP (dBm)	Max tag-to-reader distance (m)
This work	Harmonic	Stub removal	Paper	2.45;4.9	25	5
[30]	Chipless	Resonator frequency shift	Taconic CER-10-0500	2-6	0*	0.3
[31]	Chipless	Resonator frequency shift	Rogers RT/Duroid 6010.2LM	2-8	/	0.06533
[32]	Harmonic	Resonator frequency shift	Rogers RT/duroid 5880	2.78-2.89;5.56-5.78	15	0.5
[33]	UHF RFID	RSSI	No substrate	0.915	36	0.75
[34]	Chipless	Time domain reflectometry	Taconic TLX-0	2-20	/	0.3
[35]	UHF RFID	Phase difference	FR4	0.867	/	0.9
[36]	UHF RFID	Resonant frequency shift	FR4	0.90275-0.92725	36	1

* the antenna gain of the transmitter is not reported

Figure 9: Comparison with state-of-the-art passive crack sensors.

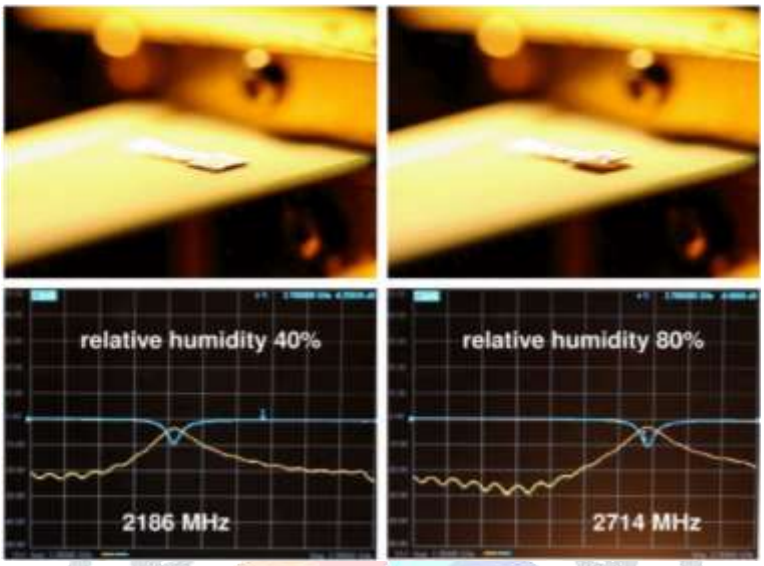

Figure 10: Bimorph paper-aluminum cantilever photograph and measured scattering parameters.

VIII. CONCLUSION

This paper discusses eco-friendly manufacturing, sustainable powering, and wireless connectivity for next-generation IoT devices to ensure that IoT technology can sustainably grow to be a part of the future connected world. Sustainable IoT devices are enabled by addressing environmental concerns using eco-friendly materials, reducing carbon footprints, and removing toxic materials from the manufacturing processes. Sustainable IoT devices are also enabled by exploiting energy harvesting and wireless power transfer technologies to eliminate the eco-toxicity of batteries or, if it is impossible to operate without a battery fully, to reduce the cost of battery replacement. Another enabler of sustainable IoT devices is novel wireless connectivity solutions compatible with battery less operation and energy harvesting schemes as, for example, retroreflective connectivity in the millimeter wave bands and beyond, higher-order modulation schemes, and wideband communication to improve the data rate and user density in the backscatter networks.

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