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Antenna Miniaturization of RF Energy Harvesting System for IoT Applications

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ABSTRACT

During the last decade the number of portable wireless electronic devices has increased dramatically in industry and commercial applications. The push is on to add Internet capability to them, often called the Internet of Things (IoT) and bringing about the challenge for design engineers to figure out how to power each of these IoT nodes efficiently and cost effectively. Typically, these devices are operated by batteries, and life-times of batteries are limited. Hence, the need for an alternative source of autonomous power to power these IoT wireless devices. Radio Frequency (RF) is an electromagnetic wave frequency that can range between 3 kHz to 300GHz. It is widely used in telecommunications and broadcasting which gives rise to wireless communications. Billions of radio frequency transmitters are used around the world that emit radio frequencies including cell phones, mobile base stations, radio and tv broadcasting stations, and handheld radios. With the availability of RF in the ambience comes the potential of harvesting that energy to produce electricity albeit a low power one since the amount of RF signal that is available in the ambient is regulated by energy commissions to a safe low level. This paper discusses the concept of antenna systems for RF energy harvesting and the challenges surrounding them. A prototype system that was designed and implemented at Universiti Tenaga Nasional is described. Potential applications to the power industry are presented.

Key words*:* RF; Energy Harvester; IoT; Miniaturization; Power Management

1. INTRODUCTION

The number of wireless IoT devices is constantly growing, and the need to reduce cost and size of the sensor imposes challenging requirements on the antenna design and manufacturing. The word IoT is an indication to whatever things capable of being connected to the internet which is far beyond the more traditionally connected things such as computers and mobile phones[1].
Wireless power transmission and harvesting power from radio frequency (RF) is an interesting alternative to power the IoT devices [2],[3]. An antenna plays a key role on the performance of RF energy harvesters where the size of antenna can result in significantly large occupied area of the design. Considering the importance of miniaturization for many space-restricted IoT applications, some important aspects related to antenna miniaturization are presented and discussed in this paper.

One of the challenges when designing an RF energy harvesting system is the antenna miniaturization. Microstrip patch antennas are extensively employed in wireless communications as they offer the advantages of light weight, low profile and simple manufacturing process [1–2]. However, a major disadvantage of conventional patch antennas is their strong dependence on the physical dimensions which determines the resonance behaviour of the antenna. The large half-wavelength size of conventional patch antennas is not desirable in modern communication systems where the compactness is of paramount importance. Furthermore, For the RF energy harvesting the free space path loss (FSPL) of a transmission link is the major loss in the system which is directly proportional to the distance and frequency of operation.

In order to reduce the free space path loss and capture more power from ambience, high gain antennas are needed in RF energy harvesting modules. According to the Friis equation, the gain of receiving and transmitting antennas can compensate for the loss of the free space:

$$P_r = P_t G_t G_r \left(\frac{\lambda}{4\pi R} \right)^2 \qquad (1)$$

Where, the distance between the receiver and transmitter is denoted by R ; G_r and G_t are the gains of the receiving and transmitting antennas; P_r and P_t are the received and transmitted power, respectively. According to (1), employing high gain antennas results to the increase of the amount of power received. Nevertheless, there is a trade-off between the antenna gain and overall antenna size. To realize high gain antenna, large electrical area, and thus, large physical area is required. This limitation makes designing RF energy harvesting systems a highly challenging task as both a compact and portable module is desired. Alternatively, in order to compensate for the limited power, broadband and multiband antennas are used. Since the RF power in the ambience is spread over a wide range of spectrum, larger amount of power is captured from multiple signal source that is adequate to drive a low power device.

Finally, while the use of high dielectric materials and increasing the Q factor of the antenna can significantly reduce the resonance frequency of the antenna, the miniaturization comes at the cost of narrow operational bandwidth, poor radiation efficiency and degradation on the radiation pattern.

Hence, a new approach is required to mitigate these limitations involving conventional approaches. The emergence of metamaterials and their exotic properties have resulted in many novel applications. Amongst them, composite right-/left-handed (CRLH) and Zeroth-order resonant (ZOR) in particular, allows for the design of artificial transmission line (TL) in which the resonant behaviour of the TL is independent from the physical length of line. By cascading multiple cells, theoretically, randomly sized antenna is possible giving an additional degree of freedom for the design of energy harvesting antenna system.

2. MATERIAL AND STRUCTURE

A. RF Energy Harvester

A RF energy harvester system typically consists of three major components as shown in the Figure 1.

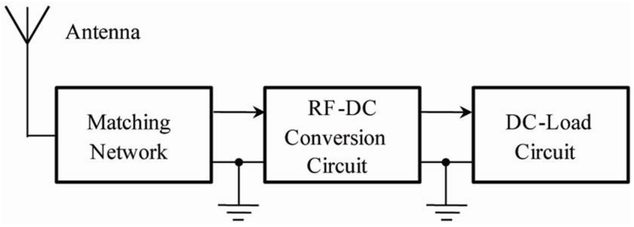


Figure 1: Typical block diagram view of a RF Energy Harvesting System

The antenna works as the heart of the system whereby it harvests RF signals from the ambient depending on the frequency the antenna was designed for. A matching impedance circuit is required to guarantee the highest possible power transfer from antenna to the rectifier circuit. The rectifier then converts the received RF signals to usable DC.

The DC output is a non-regulated output and is not maximized. This is where the power management module comes in. A power management module is introduced at the output of the rectifier to ensure the DC is boosted and to have a regulated output and stored in a battery or supercapacitor. It also plays a vital role in running an algorithm to guarantee optimum power is tracked from the incoming signal.

B. Antenna Miniaturization Design

The design of a miniaturized coplanar waveguide (CPW) fed ZOR antenna loaded by parasitic element is presented. The antenna is intended to be used in a broadband energy harvesting system by capturing energy over a wide frequency span. The geometry of the proposed antenna is shown in Figure 2 below. The parameter values of the proposed design are given in TABLE I.

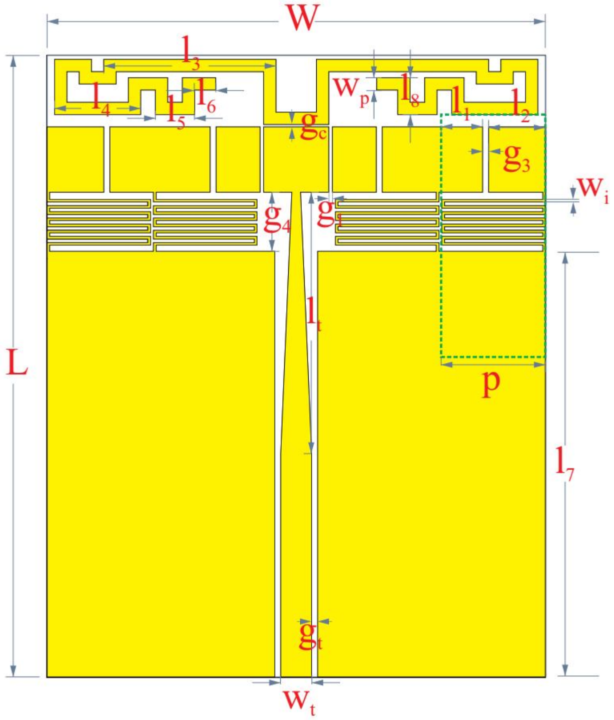


Figure 2: The layout of the proposed antenna

Table I: The optimized parameters of the proposed design

Parameter	Length (mm)	Parameter	Length (mm)
W	40.45	g_3	0.5
W_t	2.5	g_4	4.8
W_i	0.18	g_t	0.5
W_p	1.1	g_c	0.2
g_1	0.3	L	50.3
l_1	3.55	l_5	3.2
l_2	4.6	l_6	1.7
l_3	15.65	l_7	4.23
l_4	7	l_8	3
p	8.64		

The ZOR properties obtained by properly adjusting the dimensions of the unit cells targeting the GSM-1800 downlink frequency range (1805-1880 MHz) as of the main frequency of resonance. The ZOR characteristic is determined from the dispersive behaviour of the unit cell obtained from a full wave simulation using CST software. Figure 3 shows the variation on the ZOR antenna resonance at the absence of parasitic element by changing the values of left-handed inductance L_L and C_R right-handed capacitance imposed from inductive lines and distance g_4, respectively.

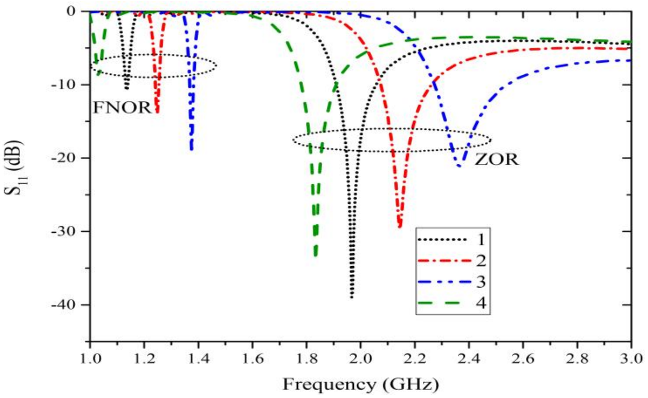


Figure 3: ZOR resonance control by respect to Δ . The variable Δ is the ratio of L_L / C_R where $\Delta_1 > \Delta_2 > \Delta_3 > \Delta_4$

Furthermore, the impact of number of unit cells on the resonance frequency and realized gain are shown in Figure 4. As is observed, the increase on the number of unit cells has minimal impact on the frequency of resonance while the gain increases considerably which indicates the high versatility of the ZOR antenna for our intended application.

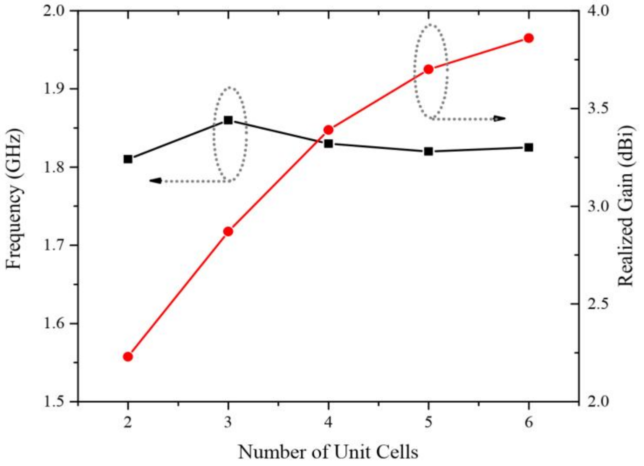
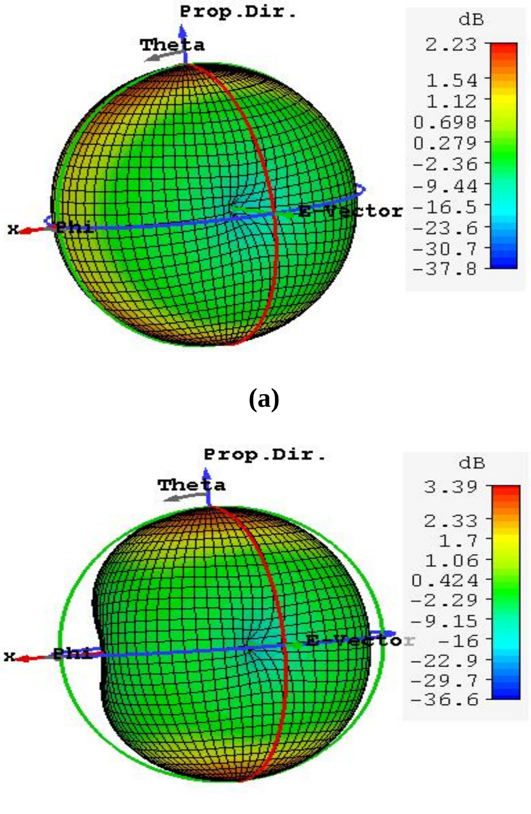


Figure 4: Relation between realized gain, resonance frequency and number of unit cells obtained from the simulation

3. RESULTS AND DISCUSSION

The 3-D farfield view of the antenna for two and four cascaded unit cells are also shown in Figure 5. A significant improvement on the limited bandwidth of antenna was obtained. In order to compensate for the low impedance bandwidth of the ZOR antenna, an additional resonance is introduced by loading a parasitic element in the form of folded dipole and simulated is shown in Figure 6.



(a)

(b)

Figure 5: 3-D farfield view of the ZOR antenna for (a) 2 and (b) 4 cascaded unit cells

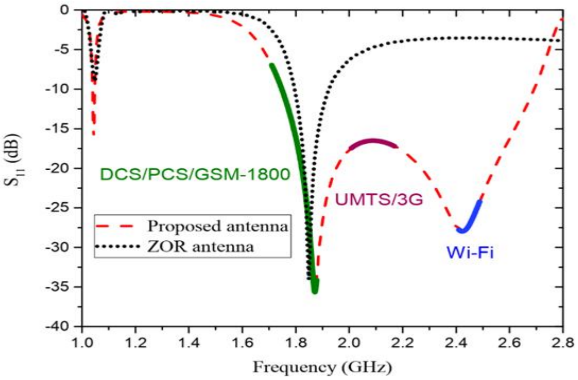
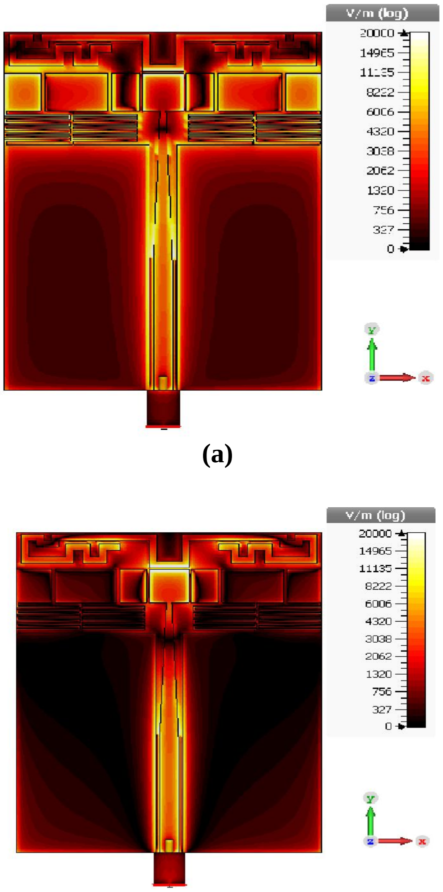


Figure 6: Comparison between the simulated return loss of the proposed antenna and ZOR antenna

As it is seen, the numerical results exhibit a wide impedance bandwidth of 951 MHz from 1.75 to 2.7 GHz covering three highly used frequency bands namely, GSM-1800, UMTS-3G and 2.4 GHz Wi-Fi bands as marked on the figure.

Moreover, The E-field intensity on the surface of the proposed design at the frequencies of 2.45 and 1.85 are demonstrated in Figure 7. It can be observed that the E-field is strong around the unit cell structures at 1.85 GHz which is the unit cell resinance frequency. One the other hand, the field intensity increases around the parasitic patch at 2.45 GHz corresponding to the resonant length of the patch.



(a)

(b)

Figure 7: E-field intensity on the surface of the proposed design at the frequencies of (a) 1.85 and (b) 2.45 GHz

A. Experimental Results

The proposed antenna was fabricated on RO4003 substrate with low loss tangent of 0.0029 and relative permittivity of 3.38. The thickness of substrate used is 20 mil. The proposed antenna occupies an area of $0.29\lambda_0 \times 0.24\lambda_0$, where λ_0 is the free space wavelength at 1.85 GHz. Figure 8 demonstrates the simulation and measured return loss results of the fabricated antenna. As is observed the antenna presents an impedance bandwidth of over 1.01 GHz corresponding to 55% of fractional bandwidth covering from 1.7 to 2.72 GHz.

Figure 9 illustrates the the fabricated antenna under the test inside the anechoic chamber. The simulated and measured radiation pattern for E- and H-plane are also shown in Figure 10. The measured gain at 1.85 and 2.45 are 2.1 and 2.38 dBi, respectively. A decent agreement between simulation and measured results is obtained confirming the effectiveness of the proposed design approach.

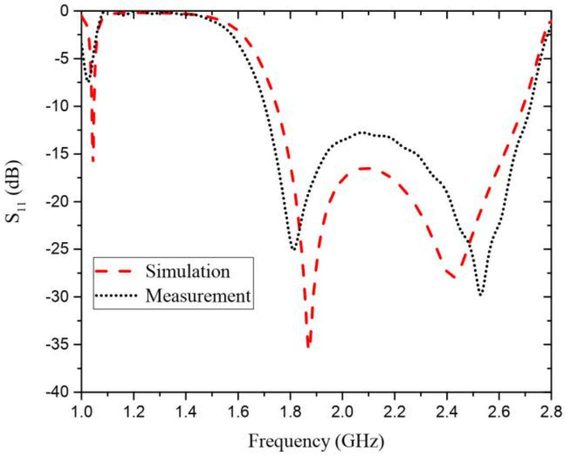


Figure 8: Comparison between the measurement and simulated return loss results of the proposed antenna

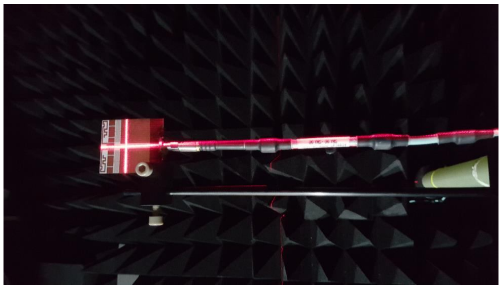


Figure 9: Photograph of the fabricated antenna under the test

B. Power Management

The power management circuit is managed by the BQ25570 integrated chip. It is a highly integrated energy harvesting power management solution which is user programmable. The IC works well with high impedance sources such as solar, thermal and RF signals. The BQ25570 is also programmed with a Maximum Power Point Traking algorithm which ensures that the input voltage does not fall below 80% of the previous open circuit voltage. Besides this, the IC is also connected with a 4.2V rechargeable battery. This will act as a storage circuit and will ensure the system is still up and running even though there is no incoming RF signals to the system. The cold start circuit requires a voltage of 330mV and once the attached battery is charged up to 1.8V, only a voltage of 100mV is required to start up the circuit. The output of the IC is a regulated output which is programmed to be at 1.8V. When there is no incoming RF and no DC output from the rectifier, the battery will discharge to power up the system and constantly providing the 1.8V output. Fig.11 below shows the rectenna which is the antenna and the rectifier connected to the BQ25570:

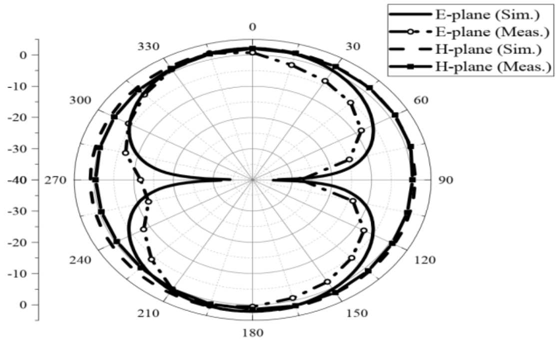


Figure 10 (a): Simulated and measured antenna radiation properties on E- planes for 1.85 GHz

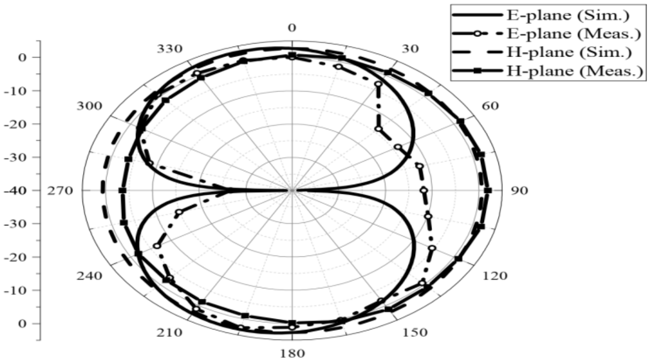


Figure 10(b): Simulated and measured antenna radiation properties on H-planes for 2.45 GHz

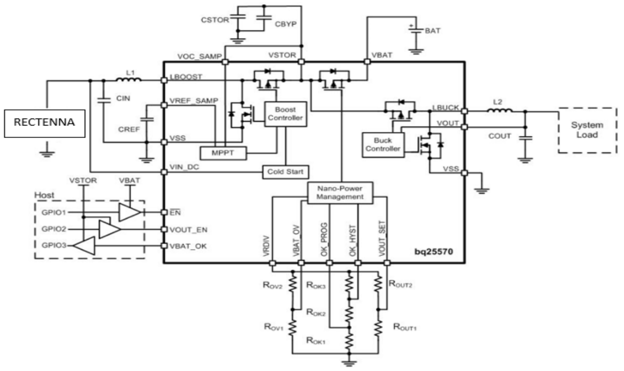


Figure 11: BQ25570 system flow with rectenna connected

The rectenna supplies the required voltage for the BQ25570 to operate. From the testing, it was noticed that with an input of 330mV, the BQ25570 took 78 seconds to start charging the battery at 4.2V. Once this happens, the output is measured to be at 1.8V. Now the input can be as low as 100mV to harvest and the battery charging and the output of 1.8V would be still available. The module was charged for 2 minutes and the incoming RF power was removed from the system. The system could run for 155 seconds and the 1.8V output was still present. The storage element provides a constant power of 1.8V to the system and ensures no interruption to load. Figure 12 below shows the testing methods and output:

Figure 12: System with 1.8V Output

C. Power Industry IoT Application

As discussed above, harvesting energy from radio-frequency waves was successfully demonstrated in a number of studies (e.g. [2] and [6]); however, the energy that can be gained from the ambient RF emissions is inherently low. This energy is reported to be at least an order of magnitude less than the available energy from other sources, such as light, vibration and temperature difference [7][8][9]. This restriction in the available energy limits the feasible applications of RF harvesting to powering only the smallest of devices, typically low-power sensor nodes. Indeed, many earlier studies of scavenging RF energy focus on the specific application of wireless sensor networks (WSNs), given that one of the biggest barriers to the wide deployment of WSN is the lack of self-sustainable/self-powered sensor nodes.

Despite this limitation, the introduction of ultra-low power technology promises to extend the viable uses of RF harvested energy beyond the traditional WSN nodes. In fact, WSNs are reminiscent (and a special case) of the more recent technology of the Internet of Things (IoT). In the realm of IoT, the sensing objects are called things, they are more versatile, and by definition can connect directly or indirectly to each other and/or the Internet. The things in IoT are not limited to sensing objects; they can even be actuators that alter their environment based on decisions taken by their own intelligence or dictated remotely from some central intelligence (usually in the cloud). Still, these things need to be charged with electric power, and providing a sustainable source of energy is ever more important.

Applications of such versatile things are much broader than those of WSNs. These applications can be found in the consumer space (consumer IoT CIoT) such as home-automation and wearable devices, and the industrial space (Industrial IoT IIoT) as can be found in manufacturing (sometimes used interchangeably with the term Industry 4.0), but also other industries such as healthcare and the retail industry. It is possible to extend this categorization to IoT in the infrastructure space, such as the power, water and transportation networks. Although the power grid is an infrastructural asset, the use of IoT in the power industry spans all the above categories and is usually associated with power subsystems of generation, transmission, distribution and utilization. Each subsystem can use the IoT in its own right.

The power industry has always utilized available technology to monitor the assets, optimize production, control operation, increase safety and enhance customer service.Two examples of early IoT applications in the electric power industry are supervisory control and data acquisition (SCADA) and advanced metering infrastructure (AMI) [10]. SCADA systems are an early version of the IoT, where they gained popularity in the power sector in the 1990s as means to automate industrial processes [11]. However, the modern IoT technology adds new dimensions to industrial operations. For example, provided with the necessary sensors, assets can be continuously monitored, and based on predictive analytics (potentially performed on the cloud), maintenance can be conducted proactively instead of reactively or on a periodic basis.

On the consumer side, IoT devices can provide the basis for active demand monitoring (for adaptive demand-response management) as well as various strategies for consumer energy efficiencies. For example, smart thermostats have been used successfully to control household heating/cooling. Nest manufacturer reported in 2015 a drop in electricity bill of 10%–12% for heating and about 15% for cooling [12]. In fact, IoT consumer solutions are the building blocks for smart buildings and smart city applications.

Perhaps the most obvious manifestation of IoT in the power industry is the notion of smart grid. To monitor the grid, analyze its performance, and then control its operation, smart grids need to deploy various types of devices at power plants, transmission lines, transmission towers, distribution centers and consumer premises. As explained in [13], the application of the IoT in smart grids can be classified into three types: (1) deploying various IoT devices for the monitoring of equipment states, (2) information collection from equipment via their connected IoT devices through the communication network, and (3) controlling the smart grid through application interfaces. IoT in this way is the enabler technology for the smart grid.

For the purpose of this paper, and given the limitation of energy in the ambient RF emissions, the viable applications can only be a subset of the example IoT applications above. Nevertheless, this subset of applications is still significant as (ultra) low power devices form a substantial portion of the IoT devices that can be used in power-industry applications. In such applications, using RF energy harvesters can eliminate or mitigate the cumbersome task of recharging or replacing the batteries in the IoT nodes, which may be a very tedious job especially in large-scale or remote deployments and may even be dangerous in some situations. IoT sensing devices can be wireless sensors, RFIDs, M2M devices, smart meters, cameras, infrared sensors, laser scanners, GPSs and various data collection devices [13]. Some of these devices are power-hungry and usually situated near constant power supplies. But other devices are not.

For example, in the area of power generation, low-power IoT nodes can be used for the monitoring of energy consumption, gas emissions and pollutants discharge. In the area of power transmission, small IoT sensors can be used for monitoring transmission lines, transmission towers and substations. In the area of power utilization, ultra-low power IoT devices can be used in smart homes for energy efficiency monitoring and management. The survey in [3] listed other RF energy harvesting applications, including RFID, which is widely used for identification, tracking, and inventory management. In this application, RFID tags, insteadof relying on the readers to activate their circuits passively, can harvest RF energy and perform communication actively. Further discussion of the possible applications of IoTin modern energy systems (low-power and otherwise) can be found in [14-15].

To conclude this section, we present a couple of use cases to illustrate the range of possible IoT applications that can serve the power utilities. We plan to test and validate the proposed RF energy harvester using one or more of these scenarios.

(i) Indoor motion analytics for smart energy management. In this application, motion sensors are distributed on selected locations throughout the industrial or residential building. Motion data are collected on the online storage of the IoT platform. Subsequently, desktop applications can be used to retrieve and visualize the online data. Motion data are analyzed to discern motion patterns, and hence decisions related to lighting, cooling and other energy facilities can be made in accordance with the performed analysis.

(ii) Online Street light monitoring. In this use case, light sensors can be used within small units and installed on street light poles. Within a local area, the units communicate in a hop-by-hop fashion towards a central unit that sends the data to the cloud-based IoT platform. The function of street light, including malfunctioning can be detected remotely in real-time using desktop or mobile apps. Other sensors can be added, and with in-circuit design, it is possible to add remote control of street lights.

(iii) Online monitoring of solar farm panels. In this application, selected sensors, such as temperature, humidity, vibration, light and voltage sensors can be mounted on small unites and fixed on solar panel poles. Within the farm, a wireless sensor network can be formed to relay the data towards a central unit (hub/gateway) from which all performance data are sent to the online storage of the IoT platform. A desktop or mobile app can be built to monitor and analyze the collected data from any point.

4. CONCLUSIONS

In this paper, some important aspects related to antenna miniaturization for energy harvesting applications have been presented and discussed. A miniaturized ZOR antenna loaded with parasitic with extended bandwidth is presented. Good performances demonstrate the validity of the proposed miniaturized design to be a desirable choice for energy harvesting applications especially IoT.

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