Autonomous Patient/Home Health Monitoring Powered by Energy Harvesting

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***Abstract*—This paper presents the design of an autonomous smart patient/home health monitoring system. Both patient physiological parameters as well as room conditions are being monitored continuously to insure patient safety. The sensors are connected on an IoT regime, where the collected data is wirelessly transferred to a nearby gateway which performs preliminary data analysis, commonly referred to as fog computing, to make sure emergency personnel and healthcare providers are notified in case patient being monitored is at risk. To achieve power autonomy three energy harvesting sources are proposed, namely, solar, RF and thermal. The design of RF energy harvesting system is demonstrated, where novel multiband antenna is fabricated as well as an efficient RF-DC rectifier achieving maximum efficiency of 84%. Finally, the sensor node is tested with different type of sensors and settings while being solely powered by a Photo Voltaic (PV) solar cell.**

***Index terms*—** E-Health, Energy harvesting, IoT, RF-DC rectifier, autonomous sensors

I. Introduction

In the realm of Internet of Things (IoT), where information is acquired by senor nodes and sent to central units for further processing, the deployment of ultra-low-power platforms is indispensable. Sensor nodes, placed in diverse environmental settings, must be able to wake up quickly, acquire information from the surrounding, send them to receiver units, go back to sleep until the next data acquisition time comes, this process must be done in the most efficient way possible. Making the sensor node power autonomous is a key element in contemporary wireless sensor networks design, i.e. the sensor node should be able to run without the need for an external power source. This power autonomy regime, can be achieved by equipping the sensor node with energy harvesting tools, as well as smart power management techniques. Energy can be harvested from different sources, depending on the surroundings of the sensor node. Solar, wind, piezoelectric, thermal and RF energy can be exploited to power sensor nodes. In order for this autonomous node to be realized and effectively deliver the task assigned to it, careful system and circuit design must be conducted to insure the node circuitry is operating at the lowest power possible, at both active and sleep mode. A typical sensor node usually spends most of its life time in sleep mode, hence, a careful power management circuitry must be deployed to insure that the power consumption and dissipation through this phase is the minimum possible. This research leverages highly analog and mixed signal techniques to increase energy efficiency of circuits and systems at both activation, sensing and sleep cycles.

II. Contribution and Scope

The IoT can find applications in various fields. In previous work we have demonstrated the feasibility of using IoT based sensors for measuring patients physiological parameters,where glucose level was measured and transferred to the patients nearby phone and gateway through nRF communication protocol [1]. The possibility of powering the wearable sensor node by RF energy harvesting have been demonstrated . In this work, we further extend this concept into a complete patient/home health monitoring system. The target users for this system can be elderly patients who would like to continue living independently, monitoring of patients recently discharged from the hospital, ICU unit patients, etc. To achieve this goal, the scope of the work presented in this paper is summarized in the following:

- Layout the architecture of the IoT based patient/home monitoring.
- Identify suitable harvesting sources for making the sensor node power autonomous.
- Design RF energy harvesting system, multiband antenna and RF-DC rectifier.
- Develop two different rectifier topologies for room and warbler sensors.

- Evaluate RF-DC rectifier performance against state of the art rectifiers.
- Evaluate the performance of autonomous sensor nodes with different sensor types and testing conditions

III. System Architecture

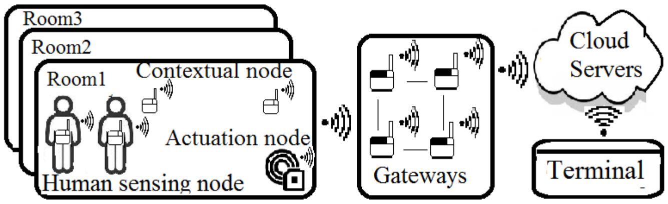

Fig. 1: Autonomous patient/home health monitoring system architecture

The architecture of the autonomous patient/home health monitoring system consists of three main parts including sensor nodes, gateways, and a back-end system as shown in Fig. 1.

A. Sensor node

The sensor node in the autonomous patient/home health monitoring system consisting of a micro-controller, a wireless module, sensor(s) or actuator(s) can be categorized into two different types described as follows. The first type is sensing nodes responsible for data acquisition and transmission. Data collected via sensors integrated into sensing nodes varies depending on sensing nodes' functionality. In the system, there are two types of sensing nodes such as contextual sensing nodes and human-related sensing nodes. Contextual sensing nodes acquire surrounding conditions data such as a room's humidity and temperature while human-related sensing nodes primarily obtain bio-signals such as human body's temperature, heart rate, and galvanic skin response data. In order to achieve comprehensive data analysis and processing, information related to the collected data such as sensor location, sensor identity, occurrence time, and protocols is captured. Acquired data and information are transmitted to a gateway via a wireless protocol. In the system the wireless protocol based on RF from Nordic Semiconductor named as nRF is utilized.

The second type is actuation nodes. Similar to sensing nodes, actuation nodes are equipped with the nRF module for transmitting the data to the system's gateway. Based on the command received from the gateway, the actuation node sends different control messages to an actuator or a group of actuators via the serial connection. In the system, the actuator comprises of a micro-controller and a relay and is powered by the electrical socket for controlling electrical devices such as fan, heater or humidifier.

Sensor nodes in the system are heavily duty cycled, set up for sleeping all the time for saving energy consumption except for the short time they spend in receiving and transmitting data. The micro-controller of sensor nodes does not perform any complex computations. Instead, complex computation will be processed at the system gateway for saving energy and reducing computation latency of the sensor node.

B. Gateway and back-end System

The system gateway with the Fog layer is constructed by an nRF wireless module, an embedded system board responsible for primary Fog services such as data processing, data storage, data transmission, and push notifications [1]–[4]. Compared to sensor nodes, the embedded system board is much more powerful in terms of processor's frequency, data storage capacity, and memory. The gateway is often powered by an electrical socket and connected to the Internet via an Ethernet module. The collected data is temporarily stored at the gateway storage. When the storage memory is completely full, the incoming data will overwrite the oldest data in the database.

In addition, the data collected via nRF at the gateway is processed at the Fog layer providing filtering methods based on pre-defined rules (e.g. several thresholds) to reduce noise and collapsed data. These threshold values are calculated based on the nature of collected data or defined by users. For example, in most of the cases, a room's temperature cannot exceed 24 degrees Celsius. When the gateway detects the temperature value sent from a sensor larger than 24 degrees Celsius , it triggers an investigation case and a fault detection case for verifying the accuracy of the obtained data and testing functionality of the sensor, respectively. In the investigation case, the gateway compares the abnormal value with a value sent from another sensing node deployed in the same room. If both values are completely different such as 24 versus 2 degrees Celsius, the abnormal values will not be sent to the Cloud. Furthermore, the gateway will write a value of "12F" to a status field used for indicating that values of two sensors in the same location at the same instant are different. The first two digits in the field indicate the identification of the sensor. In this case, the values of sensor 1 and sensor 2 are compared. If both compared values are almost similar such as 28 vs 29 degrees Celsius, the gateway will write a value of "12T" to the status field and trigger a push notification service for informing the room's users in real-time. Then, the gateway sends control signals to an actuator node which sends commands to an actuator to turn on an air-conditioner for reducing the room temperature. The push notification service, which is considered as a combination service of the Fog layer and Cloud, is used for real-time notification of abnormal situations. Depending on specific IoT applications, push notifications can be implemented more at Fog, Cloud or evenly at Fog and Cloud. In the system, the push notifications service is primarily built at the Cloud. The Fog layer is merely responsible for assigning a receiver and updating a push notification message's content.

In the fault detection case, the gateway waits for the next incoming data from the same sensor node, then compares the abnormal value with the previous and next incoming data. If the abnormal data is totally different than other values, it is neglected. If they are similar e.g. 59 versus 60 degrees Celsius , the gateway will check the status field. If the status field shows e.g. "12F", the gateway detects that the first sensing node is dysfunctional. The gateway sends the push notification to the system administrator to inform about the faulty sensor. After processing, the gateway encapsulates all related data at instant as an object and transmits it to the Cloud.

The back-end system including the Cloud and an application is responsible for storing, presenting data and helping users control the system remotely. For example, in most of the cases, users can control and change the system's threshold values mentioned above or they can directly give commands to control the system. In some cases, when the threshold values are changed dramatically or out of the normal scope (e.g. too high or too low), the system will send the notification to the system administration and show the pop-up to ask about the accuracy of the command. If the system administration confirms the command is accurate, the system will change its behaviour or threshold values based on the command. This mechanism helps to avoid misleading in providing commands. In the future, artificial intelligence will be added to the systems gateways and Cloud for enhancing decision making capability. For example, based on the event history, the data will be accumulated and analyzed for turning on a sauna's heater every 10 PM Sunday.

IV. Energy Harvesting

The practice of using wearable biomedical sensors for the continuous monitoring of physiological signals will aid the involvement of the patients in the prevention and management of chronic diseases. Assembling small biomedical sensors conveying physiological data wirelessly is conceivable as a result of the remarkable advances in ultra-low power electronics and radio communications. Nevertheless, the widespread deployment of these devices depends very much on their ability to operate for long periods of time without the need to frequently change, recharge or even use batteries. In this perspective, energy harvesting is the disruptive technology that can overlay the road in the direction of massive deployment of wireless wearable sensors for patient self-monitoring, daily healthcare, and Ambient Assisted living (AAL) lifestyle .

The source at which energy is to be harvested to supply sufficient power to run the wearable sensor nodes must fulfil the following requirements: 1) potential to supply enough power required by the sensor, 2) miniaturized in terms of size and weight since bulk/heavy wearable units are not convenient, 3) safe for human use and does not present any health hazards. Following those Guidelines, three energy harvesting sources were targeted, namely, RF, Solar, and thermal energy. For wearable body sensors RF and thermal harvesting will be used. Solar energy harvesting is excluded from being used in wearable sensors, because current commercially available PV cells -able to supply the required voltage level- are relatively large to be used in a wearable sensors. However, both solar and RF will be used in room monitoring, while RF and thermal will be utilized in body sensors.

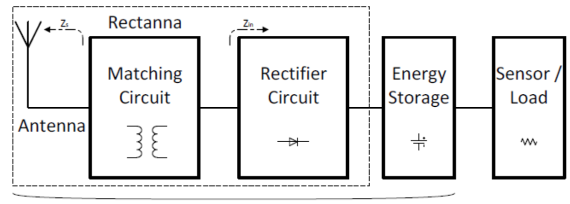

Fig. 2: RF energy harvesting system

1) RF Energy Harvesting: Radio Frequency (RF) transmissions from commercial telecommunication networks represent reliable ambient energy that can be harvested as they are ubiquitous in urban and suburban areas. The Main building blocks of the proposed RF energy harvesting system are presented in ./reffig:RF harvesting. Since the main aim of the energy harvesting system is to provide a sustainable energy supply to low power sensor nodes, it is crucial that the circuits involved in the energy harvesting process perform their tasks efficiently at the minimum possible power. As a general guideline, low power circuit and system techniques would be used in designing and optimizing the functionality of the entire system to achieve the target of low power consumption and high efficiency.

2) Miniaturised printed elliptical nested fractal multiband antenna: The selection of appropriate frequency bands is critical in RF energy harvesting applications. Scavenging RF signals from the portion of the spectrum with higher-power densities help in harvesting more energy from the ambience resulting in a more efficient harvester system. The selection of this portion of spectrum is certainly dependent on the existing signals of different standards available in the surrounding. On the basis of the citywide RF spectral surveys for EM energy harvesting conducted in [5], the higher-power densities of existing ambient signals at DTV (702 MHz), GSM 900 (880915 MHz, 925960 MHz), GSM 1800 (1.71 1.785 GHz, 1.8051.88 GHz), third generation (3G) (1.921.98 GHz, 2.112.17 GHz) and Bluetooth or Wi-Fi (2.42.468 GHz) direct the research of RF energy harvesting and its antenna design to target these specified frequency bands. A miniaturized printed elliptical nested fractal (PENF) antenna was designed to harvest RF energy form the targeted frequency bands described earlier [6]. The PENF antenna is intended to function as the receptor element in the RF energy harvesting system. This antenna exhibits a good radiation and reflection characteristics at 900 MHz (GSM), 2.4 GHz (Bluetooth/WLAN), 3.2 GHz (Radiolocation,3G), 3.8 GHz (for LTE, 4G) and additional 5 GHz band (new Wi-Fi signals) and its overall dimension is relatively small (41 mm (width) 44 mm (length) 1.778 mm (thickness)), illustrated in Fig. 4 Antennas are generally characterised by reflection and radiation properties. Reflection, which is the return loss characteristic, determines how well the antenna is capable of radiating or receiving power. Fig. 3 illustrates the return loss of the PENF antenna over the desired frequencies. As shown, the antenna exhibits a good return loss response at four major bands of 905910 MHz

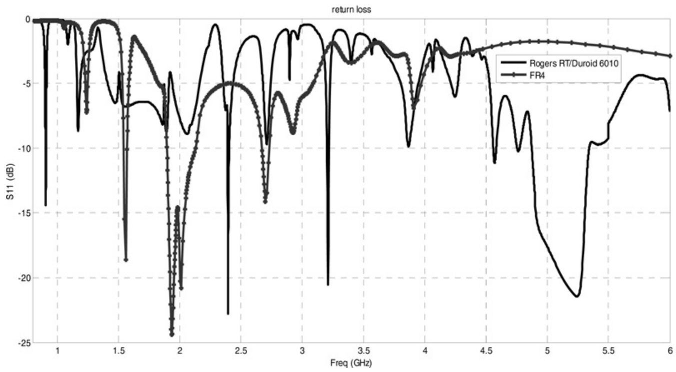

Fig. 3: Return loss response of PENF antenna designed on Rogers 6010 (r = 10.2, h = 1.778 mm) substrate against FR4 (r = 4.55, h = 1.6mm) substrate

(GSM 900), 2.4 GHz (Bluetooth/WLAN), 3.2 GHz (3G) and 4.875.33 GHz (Wi-Fi). As seen in Fig. 4, the return loss at these frequency bands is well below 10 dB ensuring proper impedance matching and reception of the antenna. In addition, the return loss is reasonable at other frequencies such as 2.7 GHz, 3.86 GHz (LTE) and 4.554.85 GHz, for which the return loss is close to 10 dB. Although the return loss is not optimal as in the major bands, it is helpful in harvesting energy from the available signals at this portion of the spectrum.

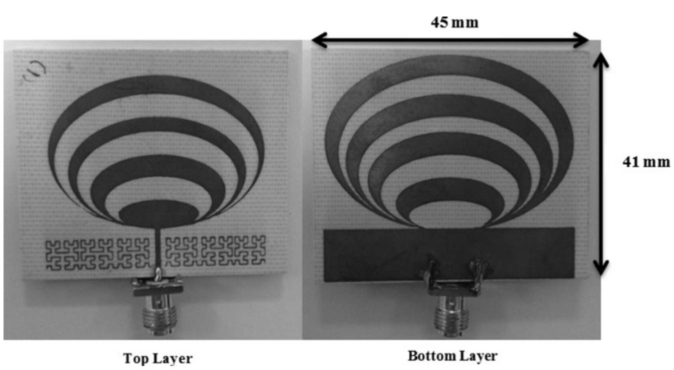

Fig. 4: Miniaturised printed elliptical nested fractal multiband antenna for RF energy harvesting

3) RF-DC rectifier: Previously, we have designed an RF-DC rectifier using Schottky diodes [7]. The rectifier proved to be 42-percent more efficient than similar exiting work in the literature. []. Schottky diodes are mainly used in RF-DC rectifiers due to their relatively low forward voltage drop caused by the extra metal layer imposed on top of the standard CMOS process. In addition, Schottky diodes reduce the response time due to their high switching speeds. However for a compact System On chip Solution (SOC), Schottky didoes can be replaced with diode-connected transistors at the expense of a slight degradation in efficiency if careful CMOS threshold cancellation techniques are followed. In this work we propose the use of two RF-DC rectifier schemes for wearable sensors and room monitoring sensors.Namely, Schottky diode based rectifiers will be implemented in room monitoring sensors were miniaturization constraints are not quite tight, while diode-connected CMOS rectifiers will be implemented in wearable senors to realize a miniaturized SOC node.

4) Efficiency analysis of rectifier circuits: Before arriving at the two rectifier topologies, an efficiency analysis was carried out to determine the factors that affect the rectifier performance and dictates its efficiency level. The RF-DC rectifier consumes the largest percentage of power among the energy harvesting system hence its efficiency decides on the overall performance of the entire system. It is also responsible for relaying the harvested power to other parts of the system so if the power is not handled properly at this stage the entire system performance will drop consequently or may mail fail to perform entirely. Rectifiers are characterized by their power conversion efficiency (PCE), which is defined as the output power P_{OUT} divided by the input power P_{IN}. The input power can be written as the sum of the output power and the loss of the rectifier P_{LOSS}, therefore, PCE can be written as follows:

$$\begin{aligned} PCE = \frac{P_{OUT}}{P_{IN}} &= \frac{P_{OUT}}{P_{OUT} + P_{LOSS}} \\ &= \frac{P_{OUT}}{P_{OUT} + N.P_{DIODE}} \end{aligned} \tag{1}$$

Where N is the number of diode stages and P_{DIODE} is the power loss of each diode which originates from the resistive loss when the current flows through the diode and can be written as follows:

$$P_{DIODE} = P_{FWD} + P_{REV} \tag{2}$$

where PFWD and PREV are forward diode loss and reverse diode loss respectively, which can be determined by the turn-on voltage and the reverse leakage current of the diode/diode-connected transistors, respectively. Reverse leakage current in conventional diode implementations is negligible,hence diode loss is roughly determined by the forward diode loss which corresponds to the diode turn-on voltage. Therefore in order to realize a large PCE, a low turn-on voltage for reducing forward diode loss is essential. However, in the case of diode-connected transistors, leakage current is not quite negligible as in the case of conventional diodes, particularly as the gate channel length decreases the effect of reverse leakage current becomes dominant. Accordingly, techniques for reducing both froward and reverse voltage drops will be implemented in designing rectifiers utilizing diode-connected transistors.

5) Schottky diode-based rectifier: Due to their low forward voltage drop Schottky diodes were used in designing the RF-DC rectifier intended to be deployed in room condition monitoring sensors. A Schottky diode is a rectifying metal-semiconductor junction which is fabricated by depositing an n-type or p-type semiconductor material on a variety of metals. While the threshold voltage of a P-N diode is around 0.6 V to 0.7 V, Schottky diodes can achieve similar performance at lower threshold levels (0.2 V to 0.3 V). The performance of the Schottky diode-based rectifier have been evaluated in previous work [7] and is summarized in Table I in the Results section.

6) Threshold cancellation-based CMOS rectifier: Conventional CMOS rectifier circuits are based on the Dickson multiplier topology, where the MOS transistors are used in the diode-connected mode. These circuits suffer from inferior PCE compared to Schottky diode-based rectifiers. To overcome the problem of high Vth,external threshold-voltage cancellation (EVC), internal threshold-voltage cancellation (IVC) and self-threshold-voltage cancellation (SVC) techniques have been used. Compared with the EVC scheme using the switched capacitor mechanism and the IVC scheme [8], the SVC scheme is much simpler and requires no additional power, possibly resulting in better PCE. In addition, the SVC scheme can obtain the best Vth cancellation efficiency at lower DC output voltage conditions, and hence at lower RF input power and voltage conditions, as compared with the IVC scheme in which gate bias voltage is generated by dividing the DC output voltage by the IVC. This is important, especially in energy harvesting applications where input RF signal level can be quite low. Based on the characteristics of the three threshold cancellation techniques discussed previously, the following results were concluded: in order to make the energy harvesting power autonomous; external Vth-cancellation scheme cannot be used. On the other hand, Internal Vth- cancellation requires no external biasing but it works effectively only under large input power conditions and it deteriorates with reduction in input power since the Vth-cancellation bias voltage is created by dividing the output voltage, which can be fairly small at low input power levels.

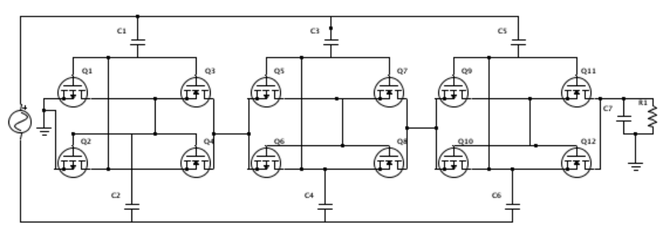

Fig. 5: Three-stage differential drive CMOS SVC-based Rectifier

The schematic shown in Fig. 5 above represents a three stage differential drive CMOS rectifier circuit using SVC technique adopted from [9]. The circuit has a cross-coupled differential CMOS configuration with a bridge structure. In this differential scheme, the gate of transistors is actively biased by a differential-mode signal. When the voltage at C1 is negative, which corresponds to the forward bias condition for the nMOS Q1 diode-connected transistor, the gate voltage of Q1, is positively biased and effectively decreases the turn-on voltage of Q1, resulting in a small ON-resistance. On the other hand, when the voltage at C1 becomes positive, which corresponds to the reverse bias condition, the gate voltage rapidly decreases, which effectively reduces the reverse leakage current.

The performance of the rectifier circuit has been evaluated at different number of stages, load conditions, and input power levels. Fig. 6 illustrates the efficiency performance of the SCV-based rectifier topology for different number of connected stages. The input power level was swept from -30 to 0 dBm and varying number of rectifier circuit stages from 1 to 7. As can inferred for figure the circuit yields higher efficiency as the number of stages increases. However, as more stages are cascaded, the peak of the efficiency curve shifts towards the higher power region. For a single stage rectifier, the peak efficiency is 78% at -20 dBm input power, while for the three stage rectifier the efficiency reaches its peak value of 84% at -15 dBm [10].

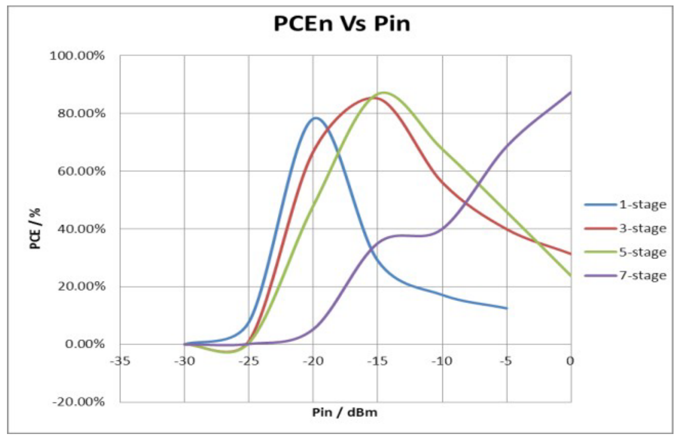

Fig. 6: PCE Vs Pin of SVC-based Rectifier

V. Results

To insure power autonomy of the wearable and room monitoring sensor nodes, the performance of the RF energy harvesting system presented above is evaluated against others available in the literature. Fig. 7 shows the PCE for the 3-stage rectifier prosed in this work for RF energy harvesting against three other rectifier topologies. Among the four rectifier topologies evaluated, the rectifier presented in this work and the one presented in [11] achieved the highest PCE value of 84%, however [11] achieved that maximum efficiency value at 5 dBm input power, while our proposed rectifier reached its maximum efficiency level of 84% at -15 dBm input power, which make more suitable low power RF energy harvesting applications. The topologies presented in [12] and [13] had inferior efficiency levels and are optimized for higher RF input power levels. Table I depicts the different harvested voltage levels from both solar and RF harvesting at different input conditions.

Several input conditions (e.g. different luminance levels) shown in Table I are experimented. Results show that when placing the solar panel at window at noon, the sensor node can harvest a large amount of energy (i.e. approximately 1500 mJ) which can fill up the energy storage in a short period of time.

In the experiments, data is collected by several temperature and humidity sensors (e.g. LM35, BME280, and DHT111)

TABLE I: Available voltage from solar and RF energy harvesting

Harvesting source	Input conditions	Harvested output voltage (V)/Current (mA)	No of modules/stages
Solar	at window	5.5/300	single module (145*145*2 mm)
Solar	room light	4.1/40	,,
Solar	dimmer room light	3.5 /≈ 0	,,
Solar	shadow place in room	1.48/0.4	,,
RF	925 MH, 5 dBm	3.3	Single stage rectifier
RF	925 MH, 0 dBm	2.1	Single stage rectifier
RF	925 MH, -10 dBm	3	Three stage rectifier
RF	925 MH, -15 dBm	2	Three stage rectifier

and transmitted to a gateway via nRF. A BME280 sensor produced by Bosch is a tiny and low-power sensor for sensing temperature, humidity, and pressure. A DHT111 sensor is for sensing temperature and humidity while LM35 is a precision integrated-circuit temperature device. These sensors are small and able to operate under a large temperature range from about -50 to 150 Celsius degrees. In the experiment, temperature and humidity are captured by BME280 and DHT111 while LM35 is merely used for capturing temperature. Results shown in Table II and Table III illustrate that BME is the most energy efficient among three sensors when sampling with the same data rate. In addition, the results highlight that by applying appropriate sensors, energy consumption of the sensor node can be saved about 15-20%.

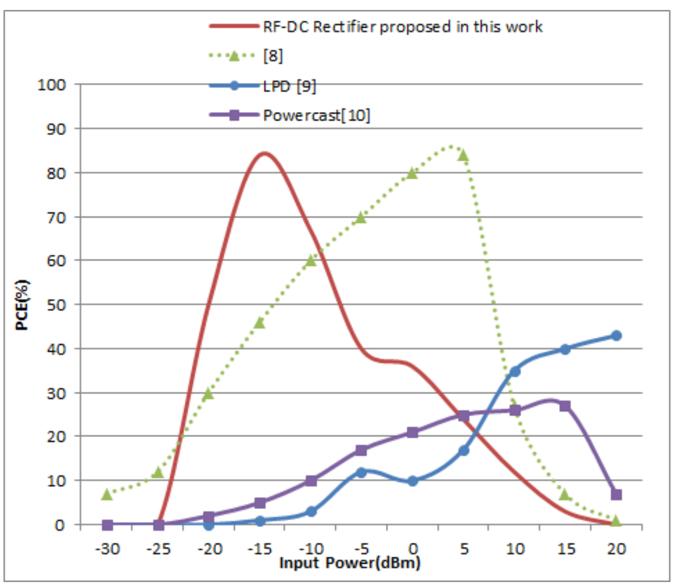

Fig. 7: Comparison between PCE results of the proposed RF-DC Rectifier, . [11] LPD prototype . [12], and commercial RF energy harvester Powercast . [13]

TABLE II: Energy consumption of the sensor node when collecting and transmitting the data with 1 sample per minute

Sensor	Voltage (V)	Current (mA)	Energy consumption (mJ)
DHT111	2.8	0.81	2.268
BME280	2.8	0.76	2.218
LM35	2.8	1.02	2.856

TABLE III: Energy consumption of the sensor node when collecting and transmitting the data with 1 sample per 10 minute

Sensor	Voltage (V)	Current (mA)	Energy consumption (mJ)
DHT111	2.8	0.78	2.184
BME280	2.8	0.73	2.044
LM35	2.8	0.98	2.744

TABLE IV: Energy consumption of the human body sensor node when collecting and transmitting the data with different data rates

Data rate	Voltage (V)	Current (mA)	Energy consumption (mJ)
1 sample/s	2.8	4.76	13.328
2 sample/s	2.8	6.18	17.304
4 samples/s	2.8	7.27	20.356

The human body sensor node consisting of a pulse heart rate sensor, a galvanic skin response sensor, and a temperature and humidity sensor is applied in the experiments. Results of the experiments shown in Table IV illustrate that the human body sensor node is energy efficient. Furthermore, results show that a total energy consumption of the human body sensor node is much larger than a total energy consumption of the contextual sensor node. The main reason is that the human body sensor node collects a large amount of human-related data with a much higher data rate. In the experiments, 1, 2, and 4 sample(s)/second data rates are used because it is required to acquire heart rate and galvanic skin response data with a minimum data rate of 1 sample/second. When applying a data rate of 1 sample/second, energy consumption of the sensor node can be saved about 23% and 35% than a data rate of 2 and 4 samples/second, respectively.

VI. Conclusion

The functionality of the autonomous patient/home monitoring system has been demonstrated. The implemented IoT-based system was a complete system starting from sensor nodes to a back-end server. Via the system, users can easily monitor and administrate their home by an Internet browser. Sensor nodes were able to acquire various data types (i.e. body temperature, heart rate, galvanic skin response, environmental data and contextual data) and wirelessly send the data to the system's gateways efficiently in term of energy consumption. Energy harvesting schemes were employed to power the sensor nodes, namely RF and solar harvesting. Novel multiband antenna and rectifier circuits were designed for the purpose of RF energy harvesting. The antenna was able to receive

RF power from five frequency bands,GSM, Wi-Fi, Bluetooth, 3G and LTE. The RF-DC rectifier achieved high PCE levels at lower RF input power levels compared to exiting work in the literature. The harvested voltage and current level were sufficient to operate the sensor node, this was demonstrated by testing the room sensor while being powered by solar PV cell.

VII. Future Work

In the future work, the sensor node capable of providing advanced functions (e.g. self-awareness and fault detection capabilities) will be constructed. The sensor node will be an advanced version of a combination of the proposed sensor nodes and our e-health sensor nodes proposed in [14]–[17] for acquiring several bio-signals such as Electrocardiography and Electromyography. Currently, it is challenging to acquire and transmit these signals by the sensor nodes which are merely powered by energy harvesting because it is required a large amount of energy for performing the tasks. Furthermore, the sensor node powered by energy harvesting for human fall detection will be designed and implemented. Similarly, the sensor node is a customized version of the proposed sensor nodes and the fall detection sensor node proposed in [18], [19]. The collected information will be analyzed and processed in the system's gateway with data mining for providing advanced system features (e.g. self-learning with intelligence, self decision making). The combination of advanced sensor nodes and gateways will enhance the whole system dramatically.

To further optimize the functionality of the REF-DC rectifier, a miniaturized PV cell will be integrated to the gate bias of diode-connected transistors, hence allowing the rectifier to operate at much lower RF input power levels. The design of the energy harvesting system will be completed by developing the thermal harvester and integrate it with the RF harvester to power wearable sensors. Aiming to further miniaturize wearable senor nodes, the use of nano sensors will also be investigated.

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References

[1] T. N. Gia et al. Iot-based continuous glucose monitoring system: A feasibility study. *Procedia Computer Science*, 109:327–334, 2017.

[2] F. Bonomi, R. Milito, J. Zhu, and S. Addepalli. Fog computing and its role in the internet of things. In *Proceedings of the first edition of the MCC workshop on Mobile cloud computing*, pages 13–16. ACM, 2012.

[3] A. Rahmani et al. *Fog Computing in the Internet of Things*. Springer International Publishing, 2018.

[4] B. Negash et al. Leveraging fog computing for healthcare iot. In *Fog Computing in the Internet of Things*, pages 145–169. Springer, 2018.

[5] J. Tavares et al. Spectrum opportunities for electromagnetic energy harvesting from 350 mhz to 3 ghz. In *ISMICT2013*, pages 126–130, 2013.

[6] M. Taghadosi et al. Miniaturised printed elliptical nested fractal multiband antenna for energy harvesting applications. *IET Microwaves, Antennas Propagation*, 2015.

[7] M. Ali et al. RF energy harvesting for autonomous wireless sensor networks. In *DTIS*, pages 78–81, 2013.

[8] J. Yi et al. Analysis and Design Strategy of UHF Micro-Power CMOS Rectifiers for Micro-Sensor and RFID Applications. *IEEE Trans. Circuit. Syst.*, 54(6):153–166, 2007.

[9] K. Kotani et al. High-efficiency differential-drive cmos rectifier for uhf rfids. $IEEE_{JJ}SSC, 17(11) : 3011 - -3018, 2009$.

[10] M. Ali et al. Enhanced efficiency threshold-cancellation based rectifier for RF energy harvesting applications. In *ICECS*, pages 803–805, 2013.

[11] I. Chaour et al. Enhanced passive rf-dc converter circuit efficiency for low rf energy harvesting. *Senors*, 44(546):1–14, 2017.

[12] P. Nintanavongsa et al. Design optimization and implementation for rf energy harvesting circuits. *IEEE J. Emerg. Sel. Top. Circuits Syst.*, 2:24–33, 2012.

[13] Powercast Corp. P2000 Series 902928 MHz Powerharvester Development Kit.

[14] A. M. Rahmani et al. Exploiting smart e-health gateways at the edge of healthcare internet-of-things: A fog computing approach. *Future Generation Computer Systems*, 2017.

[15] T. N. Gia et al. Customizing 6lowpan networks towards internet-of-things based ubiquitous healthcare systems. In *NORCHIP, 2014*, pages 1–6. IEEE, 2014.

[16] M. Jiang et al. Iot-based remote facial expression monitoring system with semg signal. In *Sensors Applications Symposium (SAS), 2016 IEEE*, pages 1–6. IEEE, 2016.

[17] T. N. Gia et al. Low-cost fog-assisted health-care iot system with energy-efficient sensor nodes. In *The 13th International Wireless Communications and Mobile Computing Conference (IWCMC 2017)*. IEEE, 2017.

[18] I. Tcarenko et al. Energy-efficient iot-enabled fall detection system with messenger-based notification. In *International Conference on Wireless Mobile Communication and Healthcare*, pages 19–26. Springer, 2016.

[19] T. N. Gia et al. Iot-based fall detection system with energy efficient sensor nodes. In *NORCAS 2016*, pages 1–6. IEEE, 2016.