Heliyon 10 (2024) e39862

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

RF power saving system for smart homes

Martynas Sapurov [a,b,*], Algirdas Baskys [a,b], Kazimieras Slivka [b], Vytautas Bleizgys [a,b], Karolis Stasys [a], Rimantas Simniskis [a,b], Valerijus Zlosnikas [b], Kęstutis Urbonas [b], Aldas Dervinis [a], Sarunas Paulikas [b], Nerijus Paulauskas [b], Raimondas Pomarnacki [b], Darius Gursnys [b], Leslav Mazeiko [b], Violeta Cymliakova [b], Pavel Piatrou [a], Justas Dilys [a,b]

[a] *State research institute Center for Physical Sciences and Technology, Sauletekio av. 3, LT-10257 Vilnius, Lithuania*
[b] *Faculty of Electronics, Vilnius Gediminas Technical University, Plytines str. 25, 10105 Vilnius, Lithuania*

ARTICLE INFO

Keywords:
RF power saving
Systems
Smart homes
Directional antenna
Sensors
Energy harvesting

ABSTRACT

In this work the investigation results of harvesting the RF energy of a 2.4 GHz Wi-Fi signal for supply of smart home leak sensors network are presented. The collected RF energy has been used as an additional source to power the sensors. The main goal of the work was to conduct research on determining the limit values of the RF signal source power and the limit distances between the RF energy harvesting system and the RF signal source, at which it is possible to harvest the RF energy and charge the energy storage capacitor. The PCB-based Yagi-Uda type antenna for RF signal receiving and a suitable RF energy harvesting system was designed for this purpose. The hardware model of the harvesting system was investigated with the designed antenna, as well as with other antennas using a signal generator and Wi-Fi router as a sources of RF signal. The obtained results demonstrate that at typical Wi-Fi router transmitting power, which is 10–17 dBm, RF energy can only be collected when the router is several tens of centimeters away from the harvesting antenna. When a router with a maximum allowed power of 20dBm is used, the distance at which it is possible to collect the RF energy, reaches 120 cm just in the case when both the transmitting and receiving antennas are Yagi-Uda directional antennas.

1. Introduction

The density of ambient radio signals, which are commonly called RF (Radio Fre-quency) signals, is constantly increasing due to the increasingly widespread use of Wi-Fi internet and other means of RF communication [1–6]. On the other hand, with the development of semiconductor technologies, there are produced more and more various purpose very low-power integrated circuits [3,7,8]. For this reason, it becomes promising to use energy of ambient RF signals to supply very low-power electronic devices. Compared to other alternative power sources such as vibration energy or photovoltaic energy, the disadvantage of RF is the low energy density, which usually does not exceed 1 μW/cm2 [9]. Meanwhile, the density of vibration energy can reach 200 μW/cm2, and the photovoltaic energy in the presence of the sun - 100mW/cm2 [9]. However, Wi-Fi RF signal energy has an important advantage - it exists all the time and especially in smart buildings [10,11]. Therefore, it seems that the energy of the Wi-Fi RF signal can be efficiently used if the

* Corresponding author. State research institute Center for Physical Sciences and Technology, Sauletekio av. 3, LT-10257 Vilnius, Lithuania.
E-mail addresses: martynas.sapurov@ftmc.lt (M. Sapurov), algirdas.baskys@vilniustech.lt (A. Baskys).

https://doi.org/10.1016/j.heliyon.2024.e39862
Received 4 March 2024; Received in revised form 3 October 2024; Accepted 25 October 2024
Available online 26 October 2024

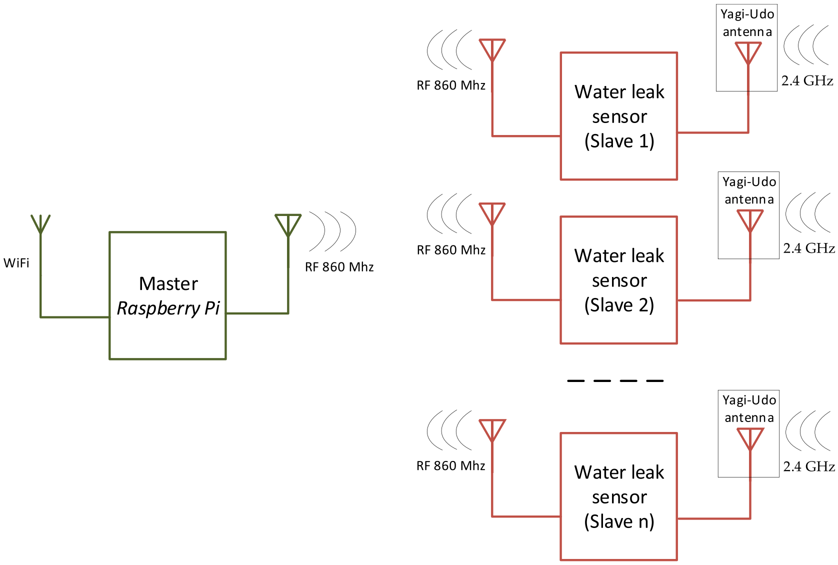


Fig. 1. Block diagram of the water leak protection system.

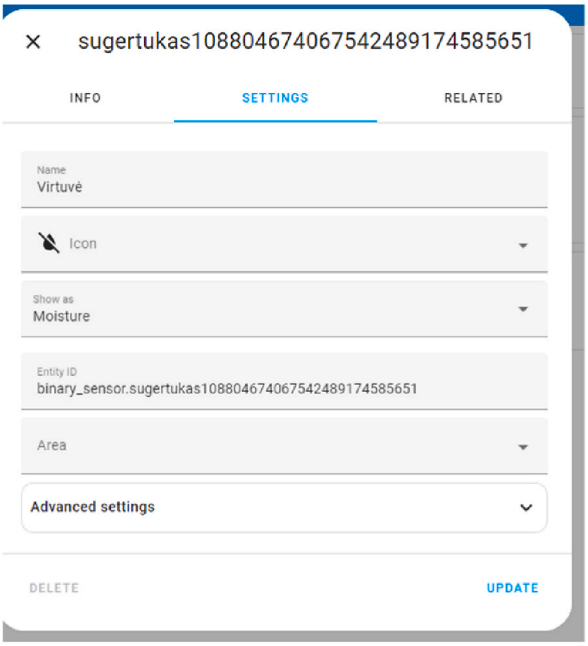


Fig. 2. Home Assistant user interface presentencing measurements of developed sensor.

electronic device consumes little power and needs it for a short time. For example, in sensors for monitoring room parameters, when data needs to be sent only when parameters measured go outside the permissible limits. Then the device can be practically all the time in sleep mode, during which the power supply current is minimal. The same applies to the cases when the monitored room parameter changes slowly and the transmitting frequency of its value can be low, and the transmitting duration is short.

Since usually it is not enough of harvested RF energy for power supply, RF can be used as an additional source to extend the life of the electronic device's power battery [1]. As a result, the battery needs to be replaced less often.

A typical ambient RF energy harvesting system includes [3]: an antenna for receiving RF signals; an impedance matching circuit for matching the impedances of the antenna with the impedance of the rectifier; a rectifier for converting the RF signal to DC; a power management circuit and a battery or capacitor that stores the harvested energy (antenna with a matching circuit and rectifier is usually called rectenna). Industry offers commercially available integrated circuits for harvested power management [12], and new integrated circuits for such purpose are also being developed [13]. As the use of Wi-Fi, which operates continuously, is rapidly increasing with the

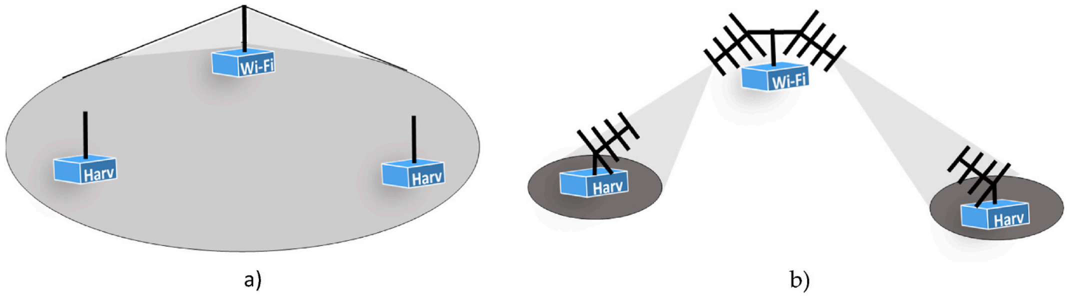


Fig. 3. Microwave energy density radiated by router with omnidirectional antenna (a) and directional antenna (b).

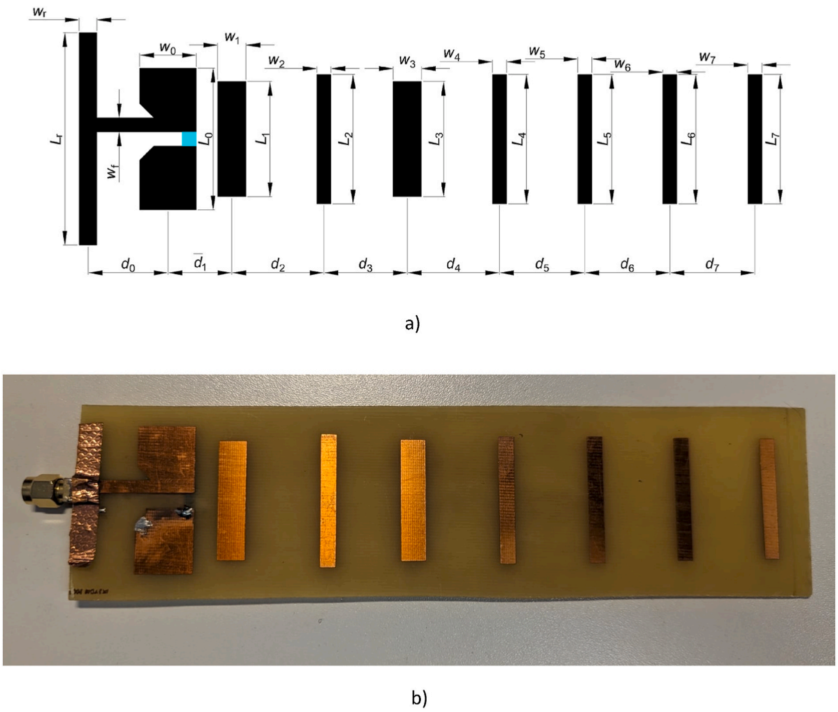


Fig. 4. Layout (a) and photo (b) of designed PCB-based Yagi-Uda type antenna for 2.4 GHz frequency.

Table 1
The dimensions of designed 2.4 GHz antenna.

Element	Width w, mm		Length L, mm		Distance d, mm	
Feeder	W_f	4.0	d_0	22.5		
Vibrator	W_0	16.0	L^0	40.0		
Reflector	W_r	5.0	L_r	60.0	d_0	22.5
Director 1	W_1	8.0	L_1	32.5	d_1	18.0
Director 2	W_2	4.0	L_2	36.5	d_2	26.0
Director 3	W_3	8.0	L_3	32.5	d_3	23.5
Director 4	W_4	4.0	L_4	36.5	d_4	26.0
Director 5	W_5	4.0	L_5	36.5	d_5	24.0
Director 6	W_6	4.0	L_6	36.5	d_6	24.0
Director 7	W_7	4.0	L_7	36.5	d_7	24.0

rise of IoT application, the focus is on harvesting RF energy in the 2.4 GHz band [14–16].

The analysis of the literature shows that there are few studies that provide data on how far from the Wi-Fi router it is possible to collect energy, e.g. Ref. [17,18]. However, research is usually carried out with one type of antenna. The originality of this work is that it has been comprehensively investigated at what distance from the Wi-Fi 2.4 GHz frequency source it is possible to harvest RF energy

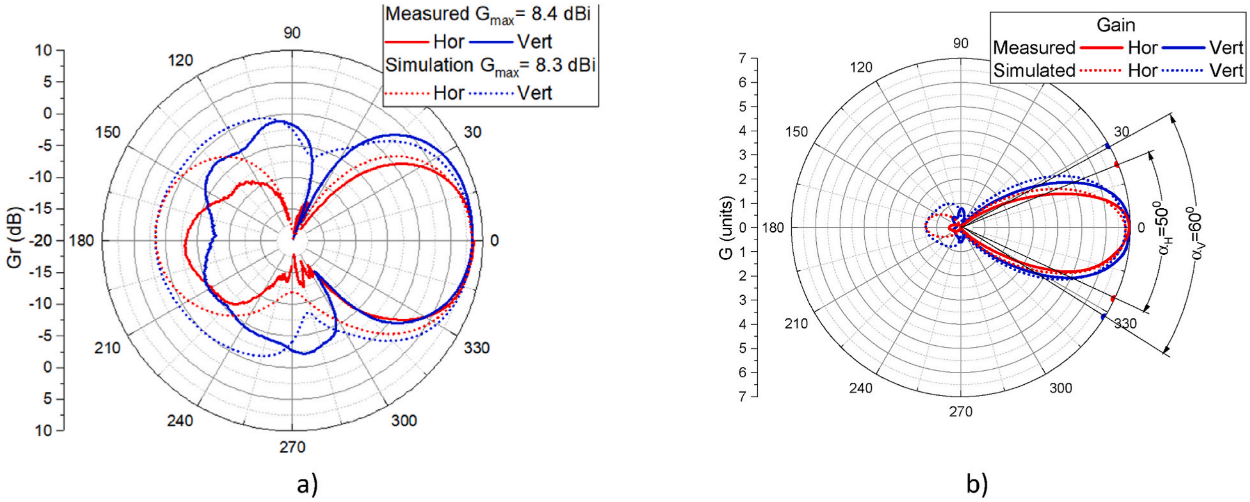


Fig. 5. Directivity diagrams: (a) in logarithmic scale, (b) in linear scale.

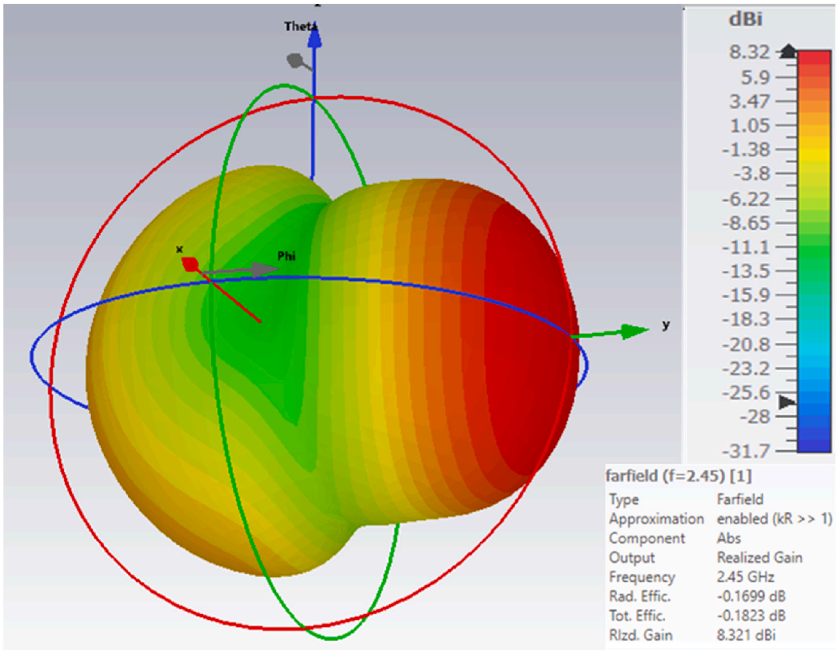


Fig. 6. Simulated with CST 3D directivity diagram of optimized Yagi_Uda antenna for Wi-Fi 2.45 GHz application.

using various antennas at various Wi-Fi transmitting powers. The practical application of harvested Wi-Fi energy for power supply of the particular network of smart water leak sensors was studied as well. These sensors are used in the water leak protection system. The collected RF energy is planned to be used as an additional source to power the sensors in this network. The directional PCB-based Yagi-Uda type antenna for RF signal receiving was designed to increase the efficiency of energy harvesting and a suitable RF energy harvesting system was adapted. The hardware model of the harvesting system was tested with the designed antenna, as well as with other 2 antenna types using a signal generator and Wi-Fi router as a sources of RF signal.

2. The structure of the leak protection system

The RF energy harvesting system was developed for smart water leak sensors of the water leak protection system. The block diagram of the water leak protection system is presented in Fig. 1. It consists of network of sensors. The 860 MHz RF link is used for the communication between sensors and central unit, while central unit operates as the device of IoT and can be accessed using Wi-Fi link. Every water leak sensor includes RF energy harvesting syste,m for 2.4 GHz Wi-Fi frequency band. It consists of antenna RF energy

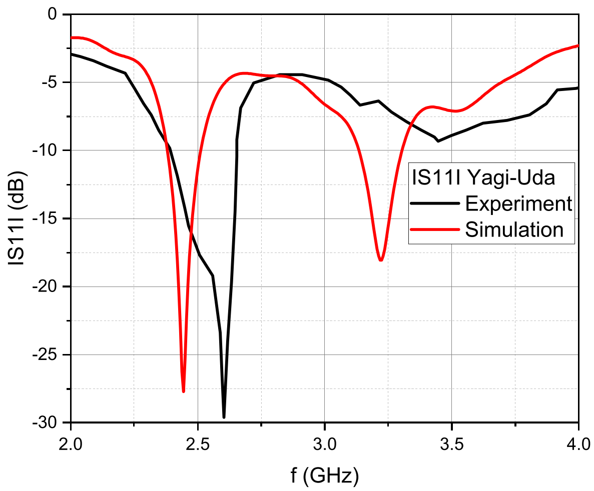


Fig. 7. Results of Yagi-Uda antenna |S11|measurements and simulations.

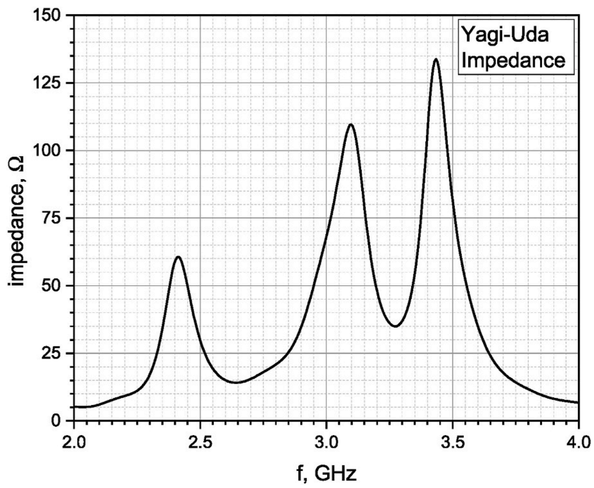


Fig. 8. Results of Yagi-Uda antenna impedance |Z|simulations.

Table 2
Received power at 2m distance, 2.4 GHz frequency, when Wi-Fi router with 1W output power is applied.

Antennas used	G_R, dBi	G_T, dBi	P_R, mW
two monopoles	5	5	0.24
monopole + Yagi-Uda	5	8.5	0.52
two Yagi-Uda	8.5	8.5	1.14

Table 3
Comparison of different antennas types suitable for 2.45 GHz frequency.

Description	Frequency range, GHz	Gain, dBi	Dimensions, mm	Remarks
Fork-Shaped 8 port [22]	0.95–2.90	3.2–7.6	220 × 220	Multiband
Microstrip patch [23]	2.15	5.6	58 × 54	Narrow band
Quasi-Yagi-Uda [27]	1.3–2.2	10.9–13.3	380 × 190	Two band
Quasi-Yagi-Uda [28]	1.8, 2.4	3.5	50 × 50	Two band
Star-shaped Yagi-Uda [33]	2.4	7.4	220 × 220 × 250	Spatial configuration
Ideal monopole [34]	2.45	6.6	76 × 10 × 10	Ideal η = 1.0
Yagi-Uda (this design)	2.3–2.6	8.4	200 × 60	Narrow band

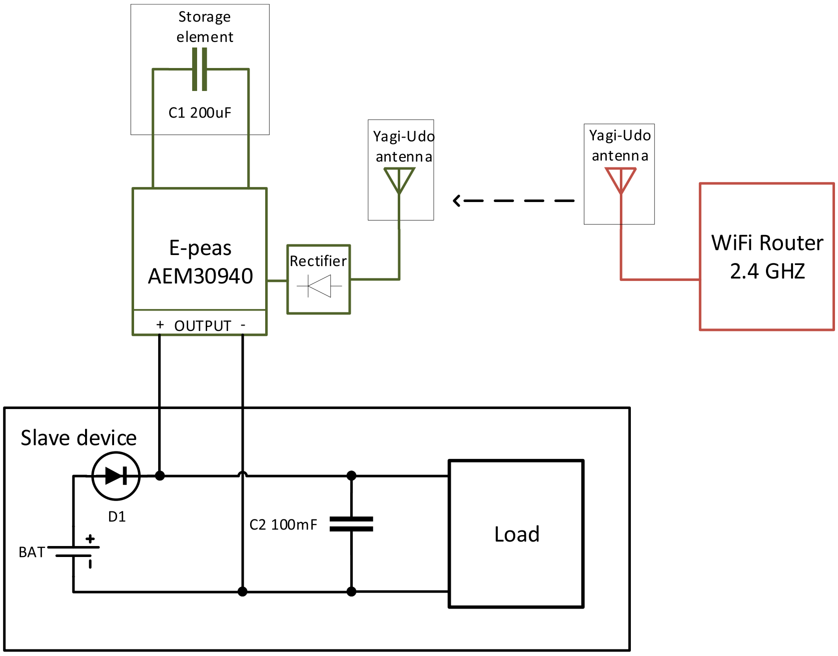


Fig. 9. Block diagram of the RF energy harvesting system.

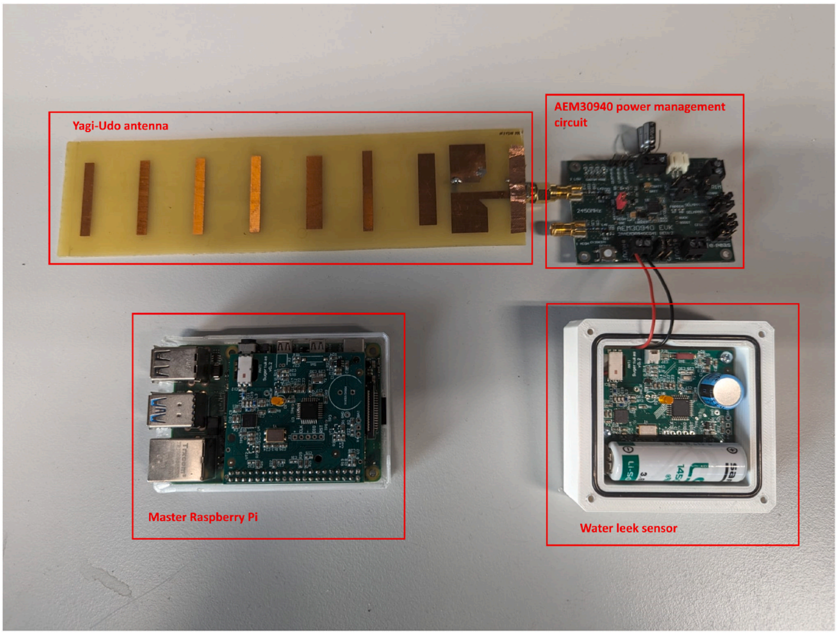
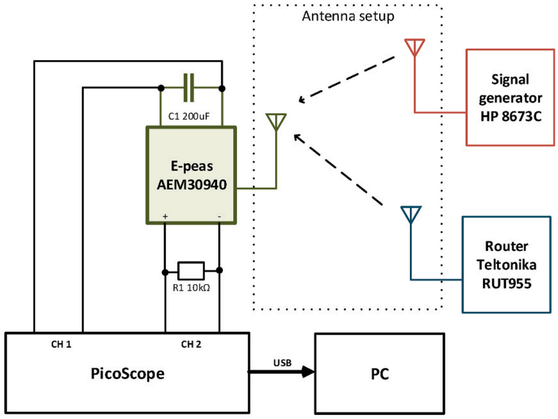


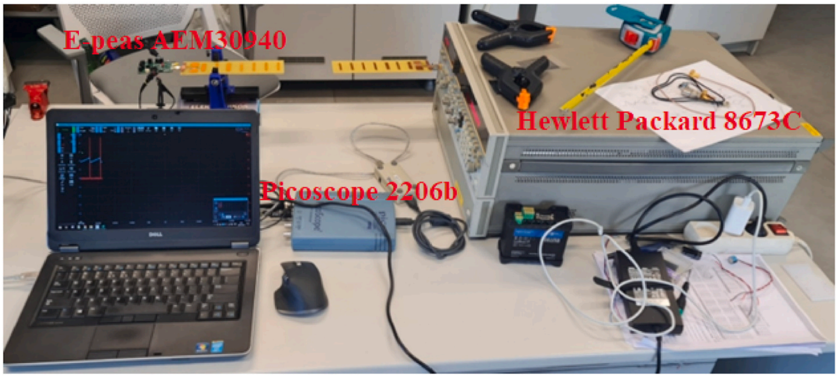
Fig. 10. Water leak sensor with the RF energy harvesting system and master of the sensor network based on the Raspberry PI.

harvesting evaluation board [19] based on AEM30940 integrated circuit [20,21] and capacitor for the saving of the harvested energy. The power management circuit receives DC voltage from the rectifier and charges the energy-harvesting capacitor with it. When the capacitor is charged, the output of the power management circuit starts supplying power to the sensor. The charging time of the capacitor is determined by the power of the received RF signal and the capacity of the capacitor. The duration for which the accumulated energy will be enough to power the sensor depends on the capacity of the capacitor and the current used by the sensor.

Developed water leak protection system consists of single master device based on the Raspberry PI microcontroller platform and up to 32 leakage sensors (slave devices) connected over 860 MHz radio frequency interface. Master device broadcasts data over radio frequency interface only during pairing process. During normal operation transmission is omnidirectional, each slave device transmits



a)



b)

Fig. 11. The block diagram (a) and photo (b) of workbench for the investigation of ambient RF energy harvesting system.

its status three times a day (every 8 h). In case leakage is detected slave transmits emergency sequence immediately. Master device consists of main operating system: Linux based main system which serves as container for two subsystems: a local MQTT (Message Queue Telemetry Transport) broker and Home Assistant. Control of all hardware interfaces, Wi-Fi and RF communications is implemented in main operating system, local MQTT broker serves for data exchange between main operating system and Home Assistant, which is employed as user interface (Fig. 2)

3. Development of PCB – based Yagi-Uda type antenna

The antenna is important component of RF energy harvesting system. The efficiency of energy harvesting depends on the directivity and efficiency of applied antenna. The Wi-Fi router monopole antennas that usually are used provide omnidirectional radiation and transmission. Therefore, the microwave density is scattered uniformly in surrounding space and results a low microwave power density. When the Wi-Fi router is applied in the configuration of energy harvesting system as energy source, the energy harvesting node is illuminated with directed energy beam and has to be located in a narrow spot of microwave radiation as illustrated in Fig. 3a. Replacing the omnidirectional antenna with high directivity antenna in the Wi-Fi router (Fig. 3b) allows to increase the power density of radiation. Employment of directional antenna in the RF energy harvesting system for receiving of RF signal allows to increase the received power as well.

Currently, PCB technology-based directional antennas for the harvesting of RF energy are popular. There are many publications devoted to such antennas. Publication [22] offers a 8-port broadband fork-shaped microstrip antenna for the frequency band 0.95–2.90 GHz with the gain 3.2 to 7.6 dBi. The dimensions of antenna are (220x220) mm. Microstrip patch antenna for the 2.15 GHz frequency is proposed in Ref. [23]. The gain of antenna is 5.6 dBi and dimensions (58x54) mm. Similar PCB-based patch antennas are described in works [24–26]. Another popular type of directional antennas for RF harvesting is the Yagi-Uda type antennas. Publication [27] proposes broadband quasi-Yagi type antenna array for frequency range 1.8–2.2 GHz. The gain of antenna 10.9 to 13.3 dBi. The dimensions of antenna array is 380x190 mm. The classic quasi-Yagi type antenna is described in Ref. [28]. It consists of two antennas that operate at 1.8 GHz (for GSM band) and 2.4 GHz (for Wi-Fi band) frequency, the gain is about 3.5 dBi, the dimensions of every antenna are about (50x50) mm. The publications ([29]; Y.-S. [30–33]) offers antenna systems consisting of multiple Yagi-Uda type antennas that form star-shaped configurations with individual antennas oriented to various directions. Such a Yagi-Uda type antenna

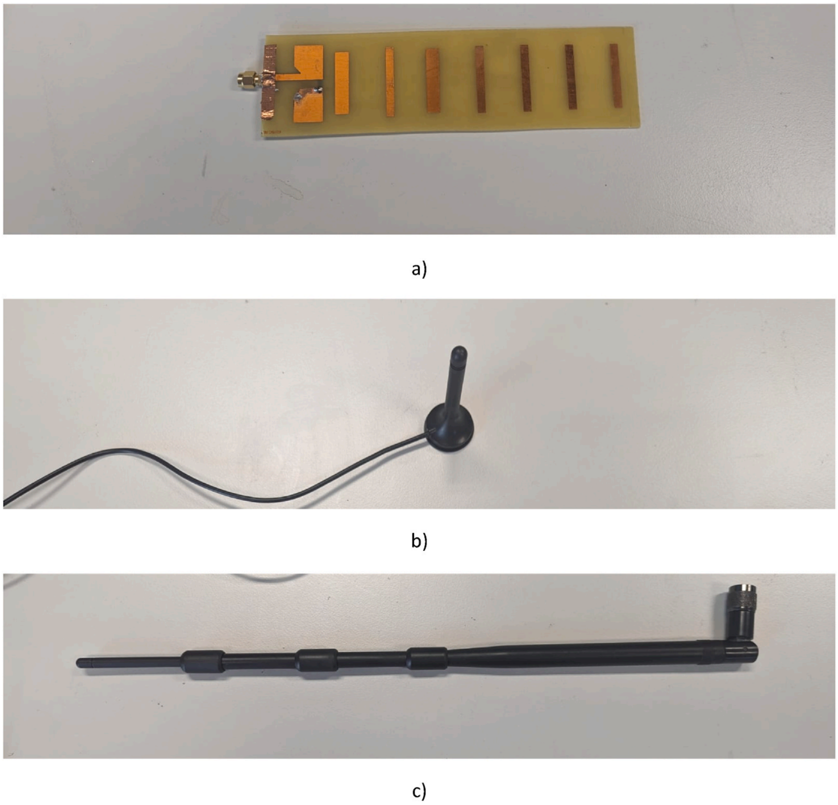


Fig. 12. Photos of designed PCB-based Yagi-Uda type antenna (a), monopole Teltonika WiFi antenna (b) and monopole D-link WiFi antenna (c).

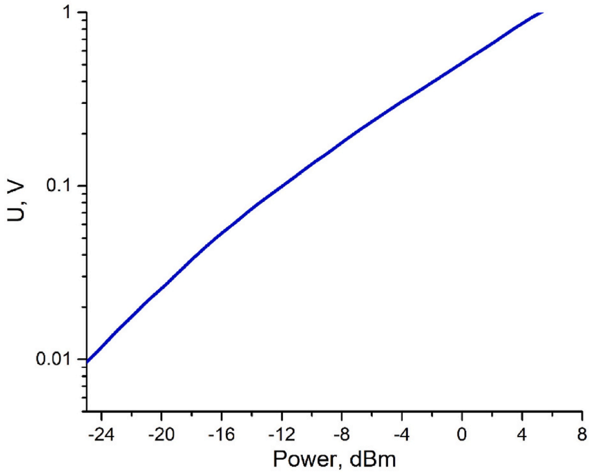


Fig. 13. The dependence of signal detector output voltage (*U, V*) on 2.4 GHz RF signal power.

systems have a high gain (around 7.4 dBi) for Wi-Fi signals coming from various directions. However, they are large, e.g. the antenna presented in Ref. [33] is spatial, the volume it occupies is 220x220x250 mm.

In the project, there was a requirement that the antenna has to be small and would have a high gain. Therefore, a single Yagi-Uda type antenna was designed to implement the harvesting system for each sensor of the sensor network. The antenna includes one reflector and 7 directing strip elements fabricated on the FR4 as printed pattern adopted for the Wi-Fi router operating on 2.4 GHz frequency as shown in Fig. 4. Dimensions of elements were calculated according wavelength. The dimensions of designed antenna are presented in Table 1.

The directivity, S11, and impedance of Yagi-Uda antenna were simulated with CST, and measured. The measured and simulated

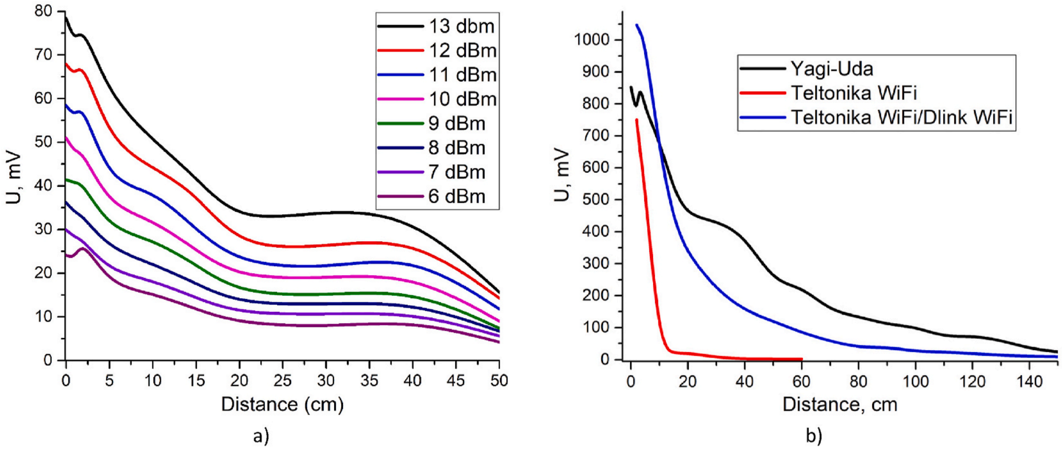


Fig. 14. The dependences of the output voltage of the RF signal detector connected to the receiving antenna on the distance between the transmitting and receiving antennas: a) RF signal source - generator HP 8673C with various output power, transmitting and receiving antennas - Yagi -Uda type b) RF signal source - Teltonika RUT955 router with output power 100 mW, black - transmitting and receiving antennas Yagi-Uda type; blue – transmitting Teltonika WiFi antenna, receiving D-Link WiFi antenna; red - transmitting and receiving antennas Teltonika WiFi antennas. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

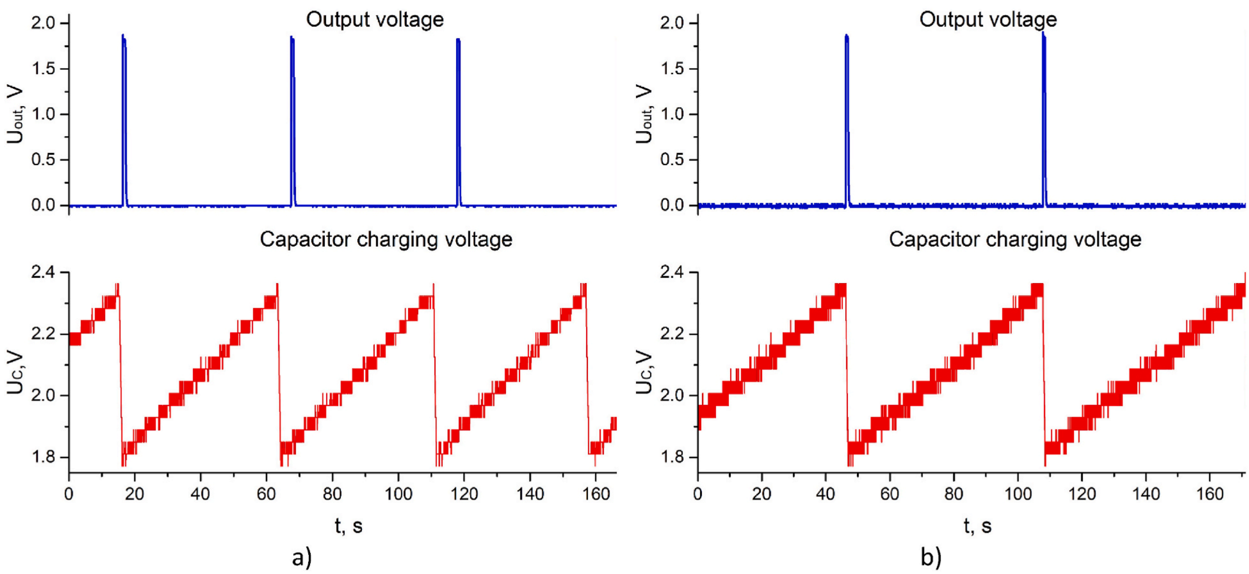


Fig. 15. Transients of capacitor charging voltage (U_C) and power management circuit output voltage (U_{out}) used for sensor supply. The RF signal source – generator HP 8673C, power 11 dBm (12.6 mW), transmitting and receiving antennas – Yagi-Uda. Distance between antennas: a) 2 cm; b) 5 cm.

directivity diagrams of designed PCB-based Yagi-Uda type antenna at 2.4 GHz frequency are presented in Fig. 5, the 3D view of simulated directivity diagram is presented in Fig. 6.

Experimental investigations of designed antenna demonstrate that measured gain on 2.4 GHz frequency is 8.4 dBi. From the directivity diagram of antenna shown in Fig. 5b, one can be concluded that angle span of radiating beam on -3dB level in horizontal plane $\alpha_H = 60^0$ and vertical plane $\alpha_V = 50^0$. Considering that spot of radiation is close to oval, from the directivity diagram, knowing angles α_H and α_V, antenna directivity D can be calculated using following equation:

$$D = \frac{16\pi}{\alpha_H \alpha_V} = \frac{16 \bullet 180^2}{\pi \alpha_H [^\circ \alpha_V [^\circ} . \quad (1)$$

From equation (1) and the values of α_H and α_V estimated using directivity diagram, the calculated directivity of antenna $D = 55$ (17.4 dB). The antenna gain G is defined as product of efficiency η and directivity D:

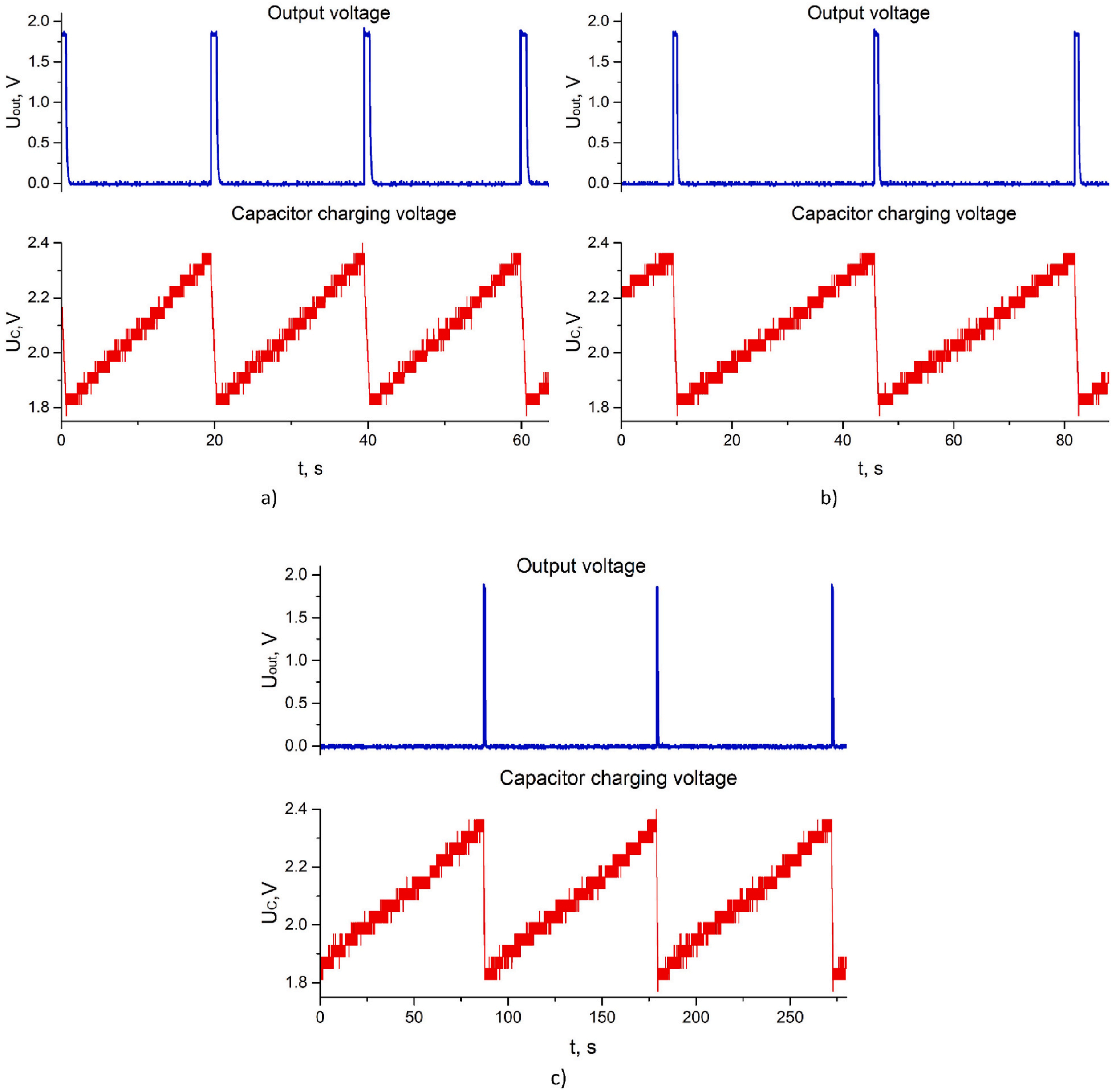


Fig. 16. Transients of capacitor charging voltage (U_C) and power management circuit output voltage (U_{out}) used for sensor supply. The RF signal source – generator HP 8673C, power 12 dBm (15.8 mW), transmitting and receiving antennas – Yagi-Uda. Distance between antennas: a) 2 cm; b) 5 cm; c) 10 cm.

$$G = D \bullet \eta. \tag{2}$$

From equation (2) and measured value of G it can be concluded that antenna efficiency is just $\eta = 0.12$. Sometimes it happens because of bad matching of the antenna with microwave port. The antenna matching was investigated, and $|S_{11}|$ was measured in 1.5–4.0 GHz frequency range. The results of $|S_{11}|$ measurements are presented in Fig. 7. It can be seen that designed Yagi-Uda type antenna is well matched in frequency range 2.4–2.6 GHz, where |S11| is below −10dB. Because the Q factor of fabricated antenna was less than in case of simulations, the frequency range of fabricated was wider than simulated. It can be concluded that low efficiency is caused by microwave losses in FR-4 PCB substrate used for the fabrication of antenna.

The impedance of simulated antenna is presented in Fig. 8. It can be noticed that it variates in the range of 30–60 Ω in the Wi-Fi 2.45 GHz frequency range.

Available on market Wi-Fi routers are equipped with monopole antennas. Theoretically at the best case, the gain of 5/8λ length monopole antennas with infinitive grounding plane $G \leq 6.6$ dBi [34]. Practically, because of loses in material of substrate it is below 5

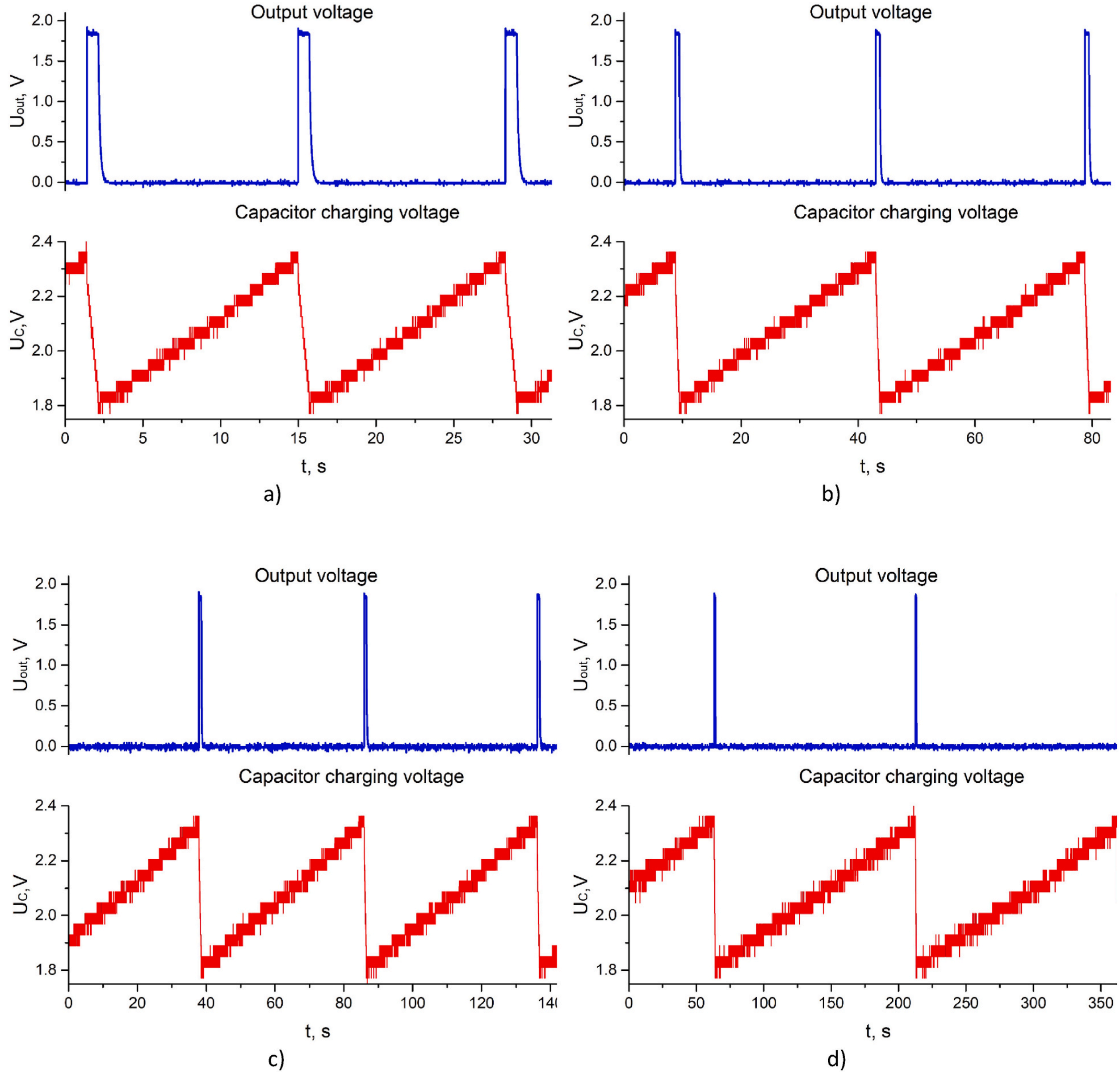


Fig. 17. Transients of capacitor charging voltage (U_C) and power management circuit output voltage (U_{out}) used for sensor supply. The RF signal source – generator HP 8673C, power 13 dBm (20 mW), transmitting and receiving antennas – Yagi-Uda type. Distance between antennas: a) 2 cm; b) 5 cm; c) 15 cm; d) 30 cm.

dBi or even lower [35]. The power P_R that is received by receiver can be calculated applying the following equation:

$$P_R = P_T G_T G_R \left(\frac{\lambda}{4\pi R}\right)^2 \tag{3}$$

where G_R is receiving antenna gain, R is the distance from antenna to router transmitter, which transmits the microwave with power P_T, G_T is transmitter antenna gain, λ is wavelength of microwave carrier frequency.

The power of Wi-Fi router transmitter can be in the range up to 1W (30 dBm). Assuming that router and microwave harvesting system are equipped with ordinary monopole antennas that are characterized by gains G_T, $G_R = 5$ dB, the received power at distance of 2 m, when $P_T = 1$W, calculated using equation (3), would be $P_R = 0.24$ mW. When our designed PCB-based Yagi-Uda type antennas with G_T, $G_R = 8.4$ dB are applied the received power would be $P_R = 1.14$ mW at the same distance. The summary of calculated values of the received power P_R by the RF energy harvesting system for the three combinations of antennas, when $P_T = 1$W and distance between sending and receiving antennas is 2m, are given in Table 2.

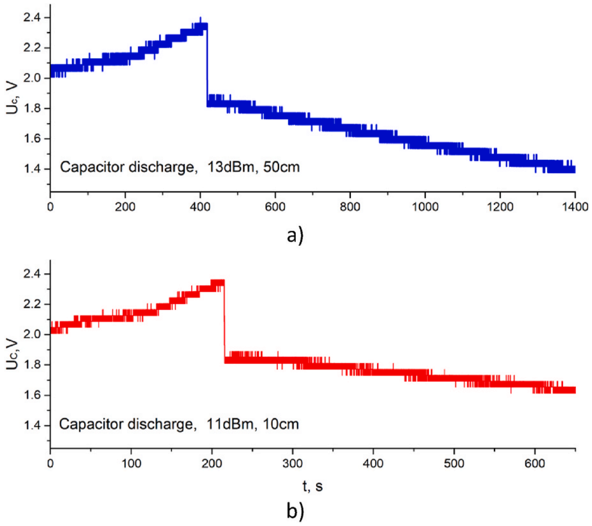


Fig. 18. Transients of capacitor charging voltage (U_C), when the capacitor cannot be fully charged, and the power management circuit is not able to provide the output voltage U_{OUT}, because the distance between the transmitting and receiving antennas is too long and, as a result the received RF power is too low.

From results presented in Table 2 it is evident that application of developed PCB –based Yagi-Uda type antenna allows to rise 5 times the power received by the energy harvesting system in comparison with the case when monopole type antennas are used. Comparison of different antennas types suitable for 2.45 GHz frequency is presented in Table 3.

4. Ambient RF energy harvesting system for supply of leak sensors

There are numerous researches on wireless sensors completely or partly powered by harvested RF energy ([36]; Z. [37–45]). Main scope of this article is to investigate whether the RF energy harvesting system using the Wi-Fi 2.4 GHz microwave energy and designed PCB-based Yagi-Uda type antennas is suitable for partial powering of water leak protec-tion system sensors. The block diagram of developed ambient RF energy harvesting system for supply of leak sensors is presented in Fig. 9.

RF energy harvesting system (Fig. 9) consists of: RF energy source - WiFi router, antenna for receiving RF signals; evaluation board for energy harvesting [21], which includes an impedance matching circuit for matching the impedances of the antenna with the impedance of the rectifier, a rectifier for converting the RF signal to DC, a power management circuit AEM30940 and a capacitor C1 that accumulates the harvested RF energy. After the capacitor is charged using the harvested RF energy, the output voltage is provided for the appropriate period by the power management circuit for the supply of the sensor. The duration when the voltage is supplied depends on the amount of energy accumulated in the capacitor and on the current consumed by the sensor. Power management circuit is capable of providing constant voltage of 1.8V–4.1V depending on the setup. Sensor itself is powered by long-life non chargeable soldered in LI SOCl2 battery, Schottky diode was incorporated in order to avoid current flow towards battery. Physical implementation of the RF energy harvesting system for the water leak sensor is presented in Fig. 10.

5. Investigation of ambient RF energy harvesting system

The operation of the RF energy harvesting system was investigated. The workbench for the investigation (Fig. 11) consists of RF signal sources - signal generator HP8673C and Wi-Fi router Teltonika RUT955 with antennas, energy harvesting board based on the power management circuit AEM30940 with antenna and oscilloscope. The high-frequency detector for the evaluation of the RF signal strength was developed as well.

The investigation was performed for the energy harvesting capacitor C1 with 200 μF capacitance, for the 10 kΩ resistor load (R1 in Fig. 11a) that served as a load whose cur-rent (180 μA) is equal to the supply current of the sensor. The results were obtained using as RF signal sources signal generator HP 8673C with output power up to 13 dBm and Wi-Fi router Teltonika RUT955 with output power 100 mW (20 dBm). The investigation was performed using designed Yagi-Uda type antenna, Teltonika WiFi antenna and D-link WiFi antenna that are presented in Fig. 12. PicoScope type oscilloscope was used for the meassurements of the signals instead of con-ventional oscilloscope due to its a large-scale data logging capability, PC served as the main experiment control unit.

In order to measure the power received by the antennas of the RF energy harvesting system, a signal detector for the frequency of 2.4 GHz was designed. It consists of a Schottky SMS-7630 high-frequency diode and a capacitor. An experimental calibration dependence of the detector output voltage on the power of the 2.4 GHz frequency signal was obtained. The signal to the detector was fed directly from the signal generator HP 8673C. The dependence is given in Fig. 13. Using the RF signal detector, the dependences of the output voltage of the detector connected to the receiving antenna on the distance between the transmitting and receiving antennas

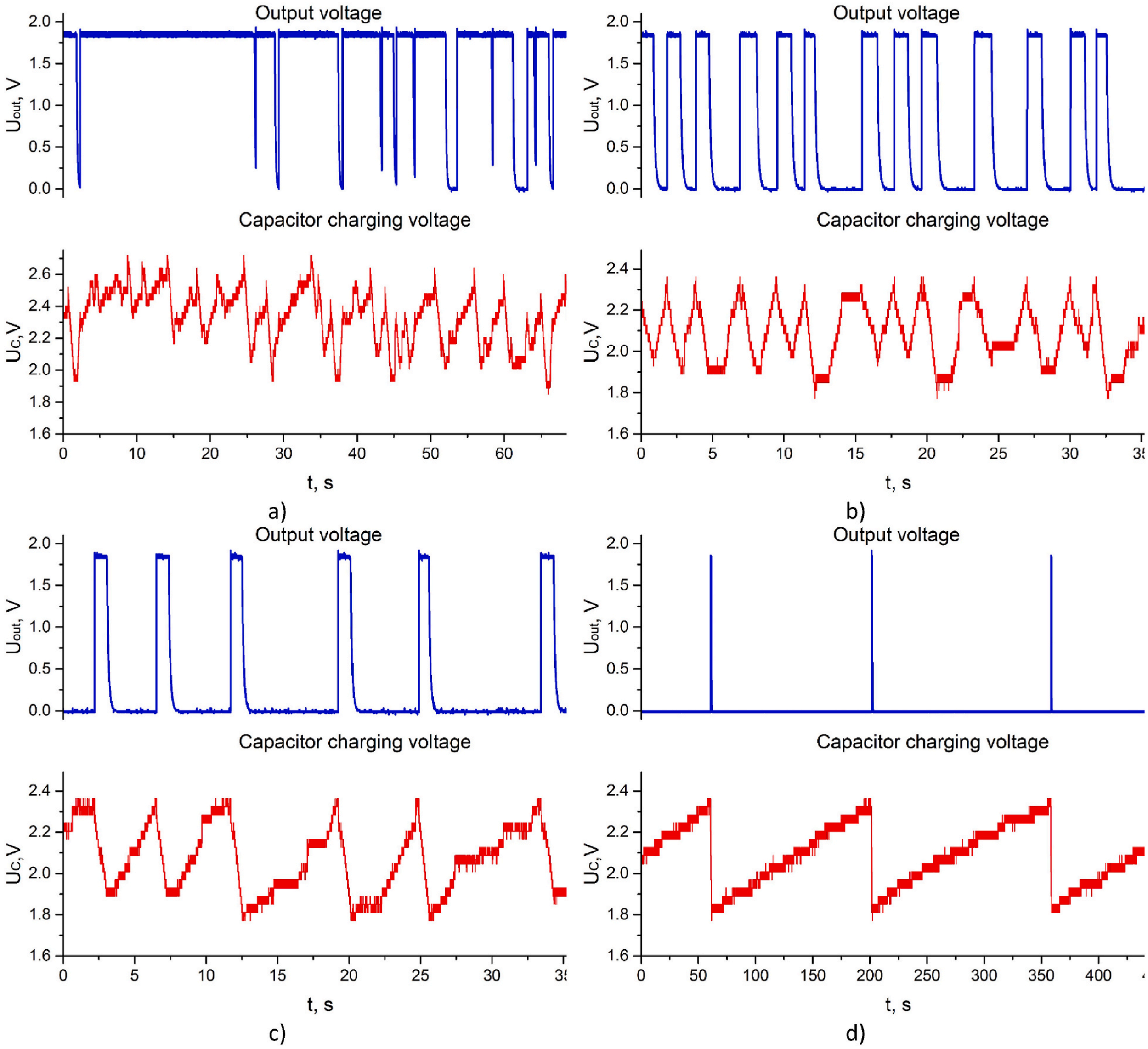


Fig. 19. Transients of capacitor charging voltage (U_C) and power management circuit output voltage (U_{out}) used for sensor supply. The RF signal source – Teltonika RUT955 router (100 mW), transmitting and receiving antennas – Yagi-Uda. Distance between antennas: a) 15 cm; b) 30 cm; c) 60 cm; d) 120 cm.

were investigated when the signal source was the signal generator HP 8673C and a Teltonika RUT955 router. The obtained results are presented in Fig. 14a and b. Using the curve presented in Fig. 14, from the curves presented in Fig. 14a and b, it can be determined the power of the signal received by the antenna. It is seen (Fig. 14a and b) that the dependences are non-monotonic, this is caused by signal reflections from various objects in the room, which is always the case in real conditions. For these reasons, as the distance increases, the detector signal does not follow the inverse proportional to square dependency on distance, because of low distances of antennas near field zone (compare the signal value in Fig. 14a for the distance of 22 cm and 32 cm) when the high directivity antenna is applied.

Energy harvesting was investigated for various types and power of the RF signal sources and distances between the transmitting and receiving antennas, using different antennas. The results of investigations for the case when our designed PSB-based Yagi-Uda type antenna was used are shown in Figs. 15–18. They present: the transition of voltage of the capacitor (U_C), which accumulates the harvested energy and the output voltage of the power management circuit (U_{OUT}) for powering the leak sensor using the energy accumulated in the capacitor.

The capacitance of capacitor C1 used for the energy harvesting was 200 μF and the load resistance was 10 kΩ (the load current $I_L =$ 180 μA). The charging time of the capacitor is 50 s and 60 s when the power of the RF signal source supplied to the transmitting antenna is 11 dBm and the distance between the transmitting and receiving antennas is 2 cm (Fig. 15a) and 5 cm (Fig. 15b), accordingly. It is seen (Fig. 15) that the accumulated energy is enough to supply voltage U_{OUT} to the sensor for 0.78 s. This duration

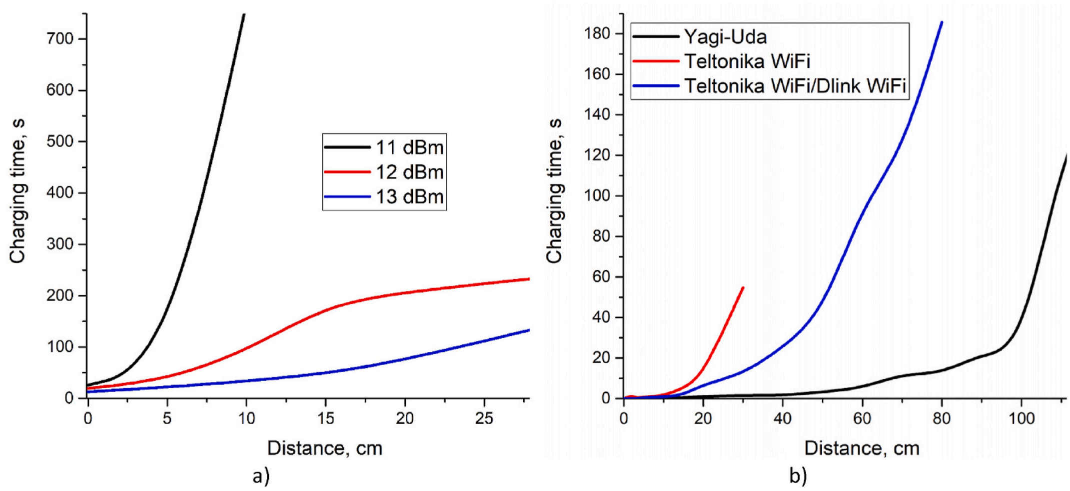


Fig. 20. The dependences of the energy harvesting capacitor C1 charging time: a) RF signal source - generator HP 8673C with various output power, transmitting and receiving antennas – Yagi-Uda type; b) RF signal source - Teltonika RUT955 router with output power 100 mW: black - transmitting and receiving antennas – Yagi-Uda type; blue – transmitting Teltonika WiFi antenna, receiving D-Link WiFi antenna; red - transmiting and receiving antennas Tetonika WiFi antennas. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

depends on the capacity of the capacitor C1 that stores the harvested energy and on the current I_L consumed by the sensor.

It is seen that the charging time of the capacitor is 20 s, 37 s, and 90 s when the power of the RF signal source supplied to the transmitting antenna is 12 dBm and the distance between the transmitting and receiving antennas is 2 cm (Fig. 16 a), 5 cm (Fig. 16b) and 10 cm (Fig. 16c), accordingly.

The results of the investigation performed at the maximum possible generator HP8673C output power of 13 dBm (20 mW) are presented in Fig. 17. The capacitor charging time decreased approximately by 40 % at 2, 5 and 10 cm distances between antennas as compared with the case when generator output power was 12 dBm (16 mW) (Fig. 16). However, at the distance of 30 cm, the charging time reached 150 s (Fig. 17d). and further increasing the distance between antennas did not always succeed in charging the capacitor. This shows that if the RF signal power is only a few tens of mW, the RF energy can be reliably collected only a few tens of centimeters from the signal source.

In cases when the power of the RF signal source is 11 dBm and distance is 10 cm (Fig. 18a) or the power of the RF signal source is 13 dBm but the distance is 50 cm (Fig. 18b), the capacitor cannot be fully charged, so a power management circuit is not able to provide the output voltage U_{OUT} because it is not enough the harvested energy to power the sensor.

Further, RF energy harvesting investigations were conducted using a more powerful RF signal source - the router Teltonika RUT955 with the output signal power of 20dBm (100 mW). The results of RF energy harvesting using our designed Yagi-Uda type antenna are presented in Fig. 19. It is seen (Fig. 19a) that when the distance between the transmitting and receiving antennas is 15 cm, the power management circuit supplies voltage to the load practically all the time, i.e., in this case, the collected RF energy is sufficient for continuous power supply of the sensor. The maximum distance at which it was still possible to harvest enough RF energy to power the sensor was 120 cm (Fig. 19d). In this case, the capacitor is charged in 160 s, and the accumulated energy is enough to power the sensor for 0.78 s.

The resulting dependences of capacitor C1 charging time on distance between transmitting and receiving antennas are presented in Fig. 20. Dependencies were obtained for the case when the signal generator HP 8673C serves as the RF source and the designed PCB-based Yagi-Uda type antennas were used for transmission and receiving are presented in Fig. 20a. Analogous dependencies when RF signal source was router Teltonika RUT955, obtained using designed Yagi-Uda type and Teltonika antennas are presented in Fig. 20b. The resulting curves show that it is possible to harvest enough 2.4 GHz RF signal energy to power the sensor briefly, but the energy harvesting system has to be close to the RF signal source. Energy can be harvested from a greater distance when designed Yagi-Uda type antennas are used for transmitting and receiving the RF signal. The maximum distance when it was still possible to harvest enough energy was 120 cm, when the RF source was a Teltonika router RUT955 with output power 100 mW.

6. Conclusions

The contribution of this work is that it experimentally investigates energy harvesting possibility in IoT applications under the actual environmental conditions determining the limit values of the RF signal source power and the limit distances between the RF energy harvesting system and source, at which it is possible to harvest the RF energy in dedicated sensor networks.

The obtained results show that application of designed directional PCB-based Yagi-Uda type antenna in the Wi-Fi router and RF energy harvesting system at 2.4 Ghz frequency increases the power received by the harvesting system up to 5 times in comparison with the case when monopole antennas are used. The maximum distance when it is still possible to harvest energy was 120 cm, when the RF signal source was a Teltonika router RUT955 (output power 100 mW) and designed Yagi-Uda type antennas were used in the router and in the RF signal energy harvesting system. However, the obtained results demonstrate that at typical Wi-Fi router transmitting power, which is 10–17 dBm, RF energy can only be collected when the router is several tens of centimeters away from the harvesting antenna. Therefore, such an energy source could serve as an additional source for the battery in individual cases.

The limitation of this work is that it was dedicated just for Wi-Fi 2.45 GHz frequency. In order to overcome this limitations harvesting possibilities for dedicated sensor networks for other RF frequencies should be investigated in future research.

CRediT authorship contribution statement

Martynas Sapurov: Writing – original draft, Supervision, Methodology, Investigation. **Algirdas Baskys:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Kazimieras Slivka:** Investigation, Conceptualization. **Vytautas Bleizgys:** Investigation, Data curation. **Karolis Stasys:** Project administration. **Rimantas Simniskis:** Methodology, Conceptualization. **Valerijus Zlosnikas:** Software. **Kęstutis Urbonas:** Software. **Aldas Dervinis:** Investigation. **Sarunas Paulikas:** Formal analysis. **Nerijus Paulauskas:** Formal analysis. **Raimondas Pomarnacki:** Formal analysis. **Darius Gursnys:** Formal analysis. **Leslav Mazeiko:** Validation. **Violeta Cymliakova:** Validation. **Pavel Piatrou:** Validation. **Justas Dilys:** Validation.

Declaration of competing interest

We confirm that neither the manuscript nor any parts of its content are currently under consideration or published in another journal and there are no conflicts of interests.

Acknowledgments

Investigation was partly funded by UAB RIM Logistika and Research Council of Lithuania.

References

[1] N.A. Eltresy, A.E.M.A. Elhamid, D.M. Elsheakh, H.M. Elhennawy, E.A. Abdallah, Silver sandwiched ITO based transparent antenna array for RF energy harvesting in 5G mid-range of frequencies, IEEE Access 9 (2021) 49476–49486, https://doi.org/10.1109/ACCESS.2021.3069409.
[2] P. Lu, C. Song, K.M. Huang, Ultra-wideband rectenna using complementary resonant structure for microwave power transmission and energy harvesting, IEEE Trans. Microw. Theor. Tech. 69 (7) (2021) 3452–3462, https://doi.org/10.1109/TMTT.2021.3067902.
[3] S. Nagaveni, S.S. Regulagadda, A. Dutta, A stage–stage dead-band compensated multiband RF energy harvester for sensor nodes, IEEE Sensor. J. 23 (5) (2023) 4940–4950, https://doi.org/10.1109/JSEN.2023.3237544.
[4] R. Ren, J. Huang, H. Sun, Investigation of rectenna's bandwidth for RF energy harvesting. 2020 IEEE MTT-S International Microwave Workshop Series on Advanced Materials and Processes for RF and THz Applications (IMWS-AMP), 2020, pp. 1–2, https://doi.org/10.1109/IMWS-AMP49156.2020.9199653.
[5] D. Surender, Md A. Halimi, T. Khan, F.A. Talukdar, Y.M.M. Antar, A 90° twisted quarter-sectored compact and circularly polarized DR-rectenna for RF energy harvesting applications, IEEE Antenn. Wireless Propag. Lett. 21 (6) (2022) 1139–1143, https://doi.org/10.1109/LAWP.2022.3159482.
[6] D. Surender, Md A. Halimi, T. Khan, F.A. Talukdar, B.K. Kanaujia, K. Rambabu, A.A. Kishk, Analysis of facet-loaded rectangular DR-rectenna designs for multisource RF energy-harvesting applications, IEEE Trans. Antenn. Propag. 71 (2) (2023) 1273–1284, https://doi.org/10.1109/TAP.2022.3231014.
[7] T. Beng Lim, N.M. Lee, B.K. Poh, Feasibility study on ambient RF energy harvesting for wireless sensor network. 2013 IEEE MTT-S International Microwave Workshop Series on RF and Wireless Technologies for Biomedical and Healthcare Applications (IMWS-BIO), 2013, pp. 1–3, https://doi.org/10.1109/IMWS-BIO.2013.6756226.
[8] Y. Wang, J. Zhang, Y. Su, X. Jiang, C. Zhang, L. Wang, Q. Cheng, Efficiency enhanced seven-band omnidirectional rectenna for RF energy harvesting, IEEE Trans. Antenn. Propag. 70 (9) (2022) 8473–8484, https://doi.org/10.1109/TAP.2022.3177492.
[9] M.M. Sandhu, S. Khalifa, R. Jurdak, M. Portmann, Task scheduling for energy-harvesting-based IoT: a survey and critical analysis, IEEE Internet Things J. 8 (18) (2021) 13825–13848, https://doi.org/10.1109/JIOT.2021.3086186.
[10] F. Fatima, P. Verma, M.J. Akhtar, Design of triple band RF energy harvesting system using monopole antenna. 2022 IEEE Microwaves, Antennas, and Propagation Conference (MAPCON), 2022, pp. 1942–1946, https://doi.org/10.1109/MAPCON56011.2022.10047521.
[11] A.U. Nabi, T. Snoussi, Z.A. Abdalkareem, A review of IoT convergence in healthcare and smart cities: challenges, innovations, and future perspectives, Babylonian Journal of Internet of Things 2023 (2023) 23–30, https://doi.org/10.58496/BJIoT/2023/004.
[12] L. Meile, A. Ulrich, P. Mayer, M. Magno, Radio frequency power transmission for self-sustaining miniaturized IoT devices: survey and experimental evaluation. 2020 International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM), 2020, pp. 132–137, https://doi.org/10.1109/SPEEDAM48782.2020.9161894.
[13] S. Nagaveni, P. Kaddi, A. Khandekar, A. Dutta, Resistance compression dual-band differential CMOS RF energy harvester under modulated signal excitation, IEEE Transactions on Circuits and Systems I: Regular Papers 67 (11) (2020) 4053–4062, https://doi.org/10.1109/TCSI.2020.3006156.
[14] M. Aboualalaa, I. Mansour, R.K. Pokharel, Energy harvesting rectenna using high-gain triple-band antenna for powering internet-of-things (IoT) devices in a smart office, IEEE Trans. Instrum. Meas. 72 (2023) 1–12, https://doi.org/10.1109/TIM.2023.3238050.
[15] A. Eid, S. Mghabghab, J. Costantine, M. Awad, Y. Tawk, Support vector machines for scheduled harvesting of wi-fi signals, IEEE Antenn. Wireless Propag. Lett. 18 (11) (2019) 2277–2281, https://doi.org/10.1109/LAWP.2019.2943250.
[16] U. Pattapu, S. Das, A 2.45 GHz rectenna system for far-field wireless power transfer/energy harvesting. 2022 International Symposium on Antennas and Propagation (ISAP), 2022, pp. 83–84, https://doi.org/10.1109/ISAP53582.2022.9998780.
[17] H. Aboueidah, N. Abbas, N. El-Nachar, A. Al-Yousef, M. Alhawari, B. Mohammad, H. Saleh, T. Assaf, M. Ismail, Characterization of RF energy harvesting at 2.4 GHz. 2017 24th IEEE International Conference on Electronics, Circuits and Systems (ICECS), 2017, pp. 446–449, https://doi.org/10.1109/ICECS.2017.8292118.
[18] F. Grante, G. Abib, M. Muller, N. Samama, Super capacitor and WiFi speed optimization for RF energy harvesting. 2022 International Conference on Electrical, Computer, Communications and Mechatronics Engineering (ICECCME), 2022, pp. 1–6, https://doi.org/10.1109/ICECCME55909.2022.9988105.
[19] AEM30940 RF 2.45 GHz Quick Start Guide EVK, V1.3, https://e-peas.com/wp-content/uploads/2021/11/QSG_EVK_AEM30940_RF_2450_V1.3.pdf, 2020.
[20] I. Bala, M.M. Mijwil, Unlocking the full potential of spectrum: a comprehensive review of cognitive radio technology, Mesopotamian Journal of Computer Science 2023 (2023) 64–71, https://doi.org/10.58496/MJCSC/2023/020.

[21] Highly efficient, regulated dual-output, ambient energy manager for AC or DC sources with optional primary battery AEM30940 (DS AEM30940 AEM30940 AEM30940 REV1.4). https://e-peas.com/wp-content/uploads/2022/09/e-peas-AEM30940-datasheet-RF-Vibration-energy-harvesting-09-22.pdf, 2022.
[22] S. Roy, R.J.-J. Tiang, M.B. Roslee, Md T. Ahmed, M.A.P. Mahmud, Quad-band multiport rectenna for RF energy harvesting in ambient environment, IEEE Access 9 (2021) 77464–77481, https://doi.org/10.1109/ACCESS.2021.3082914.
[23] K. Shafique, B.A. Khawaja, M.D. Khurram, S.M. Sibtain, Y. Siddiqui, M. Mustaqim, H.T. Chattha, X. Yang, Energy harvesting using a low-cost rectenna for internet of things (IoT) applications, IEEE Access 6 (2018) 30932–30941, https://doi.org/10.1109/ACCESS.2018.2834392.
[24] A. Contreras, B. Rodriguez, L. Steinfeld, J. Schandy, M. Siniscalchi, Design of a rectenna for energy harvesting on wi-fi at 2.45 GHz. 2020 Argentine Conference on Electronics (CAE), 2020, pp. 63–68, https://doi.org/10.1109/CAE48787.2020.9046372.
[25] C.P. Kee, L. Olule, G. Gnanagurunathan, Microstrip patch antenna and three-stage cockcroft-walton rectenna for wi-fi energy harvesting, in: 2018 IEEE International RF and Microwave Conference, 2018, pp. 242–245, https://doi.org/10.1109/RFM.2018.8846495. RFM.
[26] S.K. Sharma, A. Pratap Singh, T. Khan, A tree-shaped loaded printed antenna for dual-polarized wi-fi and sub-6 GHz 5G energy harvesting applications. 2022 IEEE 9th Uttar Pradesh Section International Conference on Electrical, Electronics and Computer Engineering (UPCON), 2022, pp. 1–4, https://doi.org/10.1109/UPCON56432.2022.9986451.
[27] H. Sun, Y. Guo, M. He, Z. Zhong, A dual-band rectenna using broadband Yagi antenna array for ambient RF power harvesting, IEEE Antenn. Wireless Propag. Lett. 12 (2013) 918–921, https://doi.org/10.1109/LAWP.2013.2272873.
[28] V. Silva, H. Paz, E. Valdés Cambero, H. Araújo, I. Casella, C. Capovilla, Dual-output quasi-Yagi antenna for out-of-band RF energy harvesting, IET Microw., Antennas Propag. 14 (2020), https://doi.org/10.1049/iet-map.2019.0541.
[29] S. Cheggour, L. Santamaria, L. Lizzi, Compact beam steering antenna based on multiple yagi-uda elements, 2021 IEEE Conference on Antenna Measurements & Applications (CAMA) (2021) 600–601, https://doi.org/10.1109/CAMA49227.2021.9703571.
[30] Y.-S. Chen, J.-W. You, A scalable and multidirectional rectenna system for RF energy harvesting, IEEE Trans. Compon. Packag. Manuf. Technol. 8 (12) (2018) 2060–2072, https://doi.org/10.1109/TCPMT.2018.2878927.
[31] R. Elkhosht, H. Hammad, A dualband rectenna design for RF energy scavenging using a modified yagi-uda antenna. 2023 International Microwave and Antenna Symposium (IMAS), 2023, pp. 154–157, https://doi.org/10.1109/IMAS55807.2023.10066948.
[32] H. Raad, A. Hammoodi, A. Issac, Reconfigurable printed yagi-uda star array for RF power transmission and harvesting systems. 2018 IEEE-APS Topical Conference on Antennas and Propagation in Wireless Communications (APWC), 2018, pp. 731–733, https://doi.org/10.1109/APWC.2018.8503775.
[33] H. Sun, J. Huang, Y. Wang, An omnidirectional rectenna array with an enhanced RF power distributing strategy for RF energy harvesting, IEEE Trans. Antenn. Propag. 70 (6) (2022) 4931–4936, https://doi.org/10.1109/TAP.2021.3138542.
[34] J.J. Carr, Practical Antenna Handbook, McGraw-Hill Companies, Incorporated, 2001.
[35] Culver, J. (n.d.). Siretta Antennas 101 eBook. https://www.siretta.com/wp-content/uploads/2022/03/Siretta-Antennas-101-eBook-1.pdf.
[36] T. Ajmal, V. Dyo, B. Allen, D. Jazani, I. Ivanov, Design and optimisation of compact RF energy harvesting device for smart applications, Electron. Lett. 50 (2) (2014) 111–113, https://doi.org/10.1049/el.2013.3434.
[37] Z. Chen, K. Chi, K. Zheng, Y. Li, X. Liu, Common throughput maximization in wireless powered communication networks with non-orthogonal multiple access, IEEE Trans. Veh. Technol. 69 (7) (2020) 7692–7706, https://doi.org/10.1109/TVT.2020.2989455.
[38] M.-T. Chiu, C.-Y. Chiu, C. Ng, L.-O. Wong, S. Shen, R. Murch, An ambient RF powered wireless sensor system, IEEE Open Journal of Antennas and Propagation 3 (2022) 1382–1393, https://doi.org/10.1109/OJAP.2022.3225169.
[39] D. De Donno, L. Catarinucci, L. Tarricone, An UHF RFID energy-harvesting system enhanced by a DC-DC charge pump in silicon-on-insulator technology, IEEE Microw. Wireless Compon. Lett. 23 (6) (2013) 315–317, https://doi.org/10.1109/LMWC.2013.2258002.
[40] A. Dolgov, R. Zane, Z. Popovic, Power management system for online low power RF energy harvesting optimization, IEEE Transactions on Circuits and Systems I: Regular Papers 57 (7) (2010) 1802–1811, https://doi.org/10.1109/TCSI.2009.2034891.
[41] X. Liu, K. Zheng, X.-Y. Liu, X. Wang, Y. Zhu, Hierarchical cooperation improves delay in cognitive radio networks with heterogeneous mobile secondary nodes, IEEE Trans. Mobile Comput. 18 (12) (2019) 2871–2884, https://doi.org/10.1109/TMC.2018.2885268.
[42] M. Pinuela, P.D. Mitcheson, S. Lucyszyn, Ambient RF energy harvesting in urban and semi-urban environments, IEEE Trans. Microw. Theor. Tech. 61 (7) (2013) 2715–2726, https://doi.org/10.1109/TMTT.2013.2262687.
[43] A.P. Sample, D.J. Yeager, P.S. Powledge, A.V. Mamishev, J.R. Smith, Design of an RFID-based battery-free programmable sensing platform, IEEE Trans. Instrum. Meas. 57 (11) (2008) 2608–2615, https://doi.org/10.1109/TIM.2008.925019.
[44] R. Shigeta, T. Sasaki, D. Quan, Y. Kawahara, R. Vyas, M. Tentzeris, T. Asami, Ambient RF energy harvesting sensor device with capacitor-leakage-aware duty cycle control, Sensors Journal 13 (2013) 2973–2983, https://doi.org/10.1109/JSEN.2013.2264931. IEEE.
[45] R. Vyas, B. Cook, Y. Kawahara, M. Tentzeris, E-WEHP: a batteryless embedded sensor-platform wirelessly powered from ambient digital-TV signals, Microwave Theory and Techniques, IEEE Transactions On 61 (2013) 2491–2505, https://doi.org/10.1109/TMTT.2013.2258168.