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Practical Remarks on Power Consumption in WLAN Access Points

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***Abstract*—The article presents the power consumptions measurements performed for three wireless routers operating in IEEE 802.11n standard. A typical consumer-class device Asus RT-AC66U was chosen, an operator-class Gateworks Laguna GW2387 and a router built based on the Raspberry Pi3 platform. The aim of experiments was to test the influence of the beacon interframe interval, a client association (joining) in the network and the transmission itself, on the lifetime of battery-powered devices. Theoretical calculations were also performed for the influence of the analyzed scenarios on the battery-powered devices.**

***Keywords*—IEEE 802.11n, beacon, power consumption, Raspberry Pi3, OpenWrt**

I. Introduction

NOWADAYS the WLAN networks are by far the most frequently used Wireless networks. At the moment, the most popular standard is IEEE 802.11n [1] that offers satisfactory throughput at relatively low prices of devices. Although IEEE 802.11n networks are capable of operating in 2.4 GHz or 5 GHz bands, experience indicated that users are more likely to use the 2.4 GHz band. On the one hand it is caused by ignorance, on the other hand many users still posses legacy devices incapable of handling the upper band. Due to a large number of WLAN networks operating in the lower ISM (*Industrial, Scientific, Medical*) band, the use of a 40 MHz wide channel is problematic. For an arbitrary user a wireless network with the throughput reaching 540 Mb/s at the bandwidth (BW) of 40 MHz or 260 Mb/s at BW=20 MHz and with the use of MIMO 4×4 (*Multiple Input Multiple Output*) appears to be ample. In most cases, the bottleneck in the access to Internet is the Internet Service Provider's (ISP) network. The prevalence of WLAN networks is also explained by its ease of setting up and configuring. Obviously, this setup ease implies that most of them operate at standard settings that implies, among others, a maximum radiated power, which quite often is unjustified and generates unnecessary interference to other networks operating at the same area.

A potential designer and administrator of WLAN networks has access to a broad range of devices available in the market. They may choose from professional access points, SOHO (*Small Office Home Office*) access points or run a WLAN network based on a microcomputer such as Raspberry Pi3 (RPi3) or even on their own smartphones. The article presents results of the energy consumption by access points in different working phases: the idle mode (with only *beacon* frames being sent), the user association (joining) in the network and the data transmission. The energy consumption by network devices is a vital aspect of their work, often underestimated by end users. In the era of Internet of Things [2], devices are often required to operate on batteries, which makes the knowledge on the power intake during their different operating stages a valuable tool that allows to optimize their settings and, in effect, prolong their battery lifetime.

Investigations were performed for the following devices (fig. 1):

- Asus RT-AC66U (SOHO applications),
- Gateworks Laguna GW2387 (professional applications),
- Raspberry Pi3 (SOHO applications).

Asus RT-AC66U is a gigabit router with a double-band wireless AC1750 module. The device is equipped with a Broadcom BCM4706 processor running at a 600 MHz clock and 256MB of RAM memory, with to two Broadcom network interface cards (NIC) (BCM4360 and BCM4331) that allow for operation in the 3×3 MIMO mode [3].

Gateworks Laguna GW2387 is a single-board computer applicable as a basis for constructing access points [4]. It is equipped with Cavium CNS3410 processor running at 300MHz clock and 256 MB of RAM memory. It has a built-in R52N-M WLAN NIC, that enables working in the 2×2 MIMO mode allowing throughputs up to 300Mbit/s.

Raspberry Pi3, similarly to Laguna, is a single-board computer. On board of RPi3 there is a Broadcom BCM2837 processor with a 64-bit quad-core ARM-8 Cortex-A53 CPU, running at a clock of 1.2 GHz and 1 GB of RAM memory. On top of that there is an integrated BCM43438 wireless LAN radio module and a Bluetooth Low Energy (BLE) module [5]. The NIC does not support MIMO.

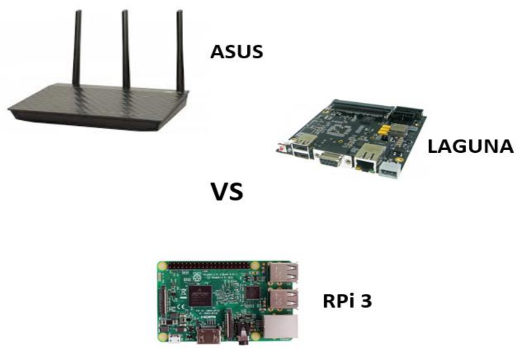

Fig. 1 WLAN routers used in the power consumption investigations: Asus RT-AC66U, Gateworks Laguna GW2387 and Raspberry Pi3

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The selection of the above mentioned devices was not accidental. The Asus router is a very common device featured by its considerable efficiency which it makes a frequent choice of SOHO, non-commercial users. Ruterboard Laguna, on the other hand, is a representative of operator-class devices and requires from its administrator vast knowledge to install expansion cards, append/update drivers for the operating system and even build one's own compilations. The single-board Raspberry Pi3 computer, in turn, was chosen due to its great popularity as well as the fact that it is often picked for building media gateways in Internet of Things networks.

The Asus device was working under the AsusWRT operating system control (a partially closed software on a GPL license), whereas the other two devices, Gateworks and Raspberry, under the OpenWrt/Lede operating system control [6]. All the wireless routers were configured for working in the IEEE 802.11n standard (in the "n-only" model, incompatible with previous IEEE 802.11 standard versions), with EIRP (*Equivalent Isotropic Radiated Power*) equal to 20dBm (unless specified otherwise, as in chapters II or V). During the experiment, the devices were powered by the Keithley 2231A-30-3 laboratory power supply unit, whereas the energy consumption was measured with the use of the Tektronix DMM7510 multimeter that allowed for measurements at 7½-digit precision and a USB data storage.

II. THE BEACON FRAME TRANSMISSION

The purpose of the first measurements was to determine the increase in the power consumed from the source by the access points while broadcasting a single beacon frame, compared to the idle state. For each wireless router a 1-second long measurement was taken with the laboratory multimeter capable of logging 100,000 samples per second, meaning that within every 1 ms a hundred samples were acquired. The experiments were performed at three EIRP levels: 20, 17 and 0 dBm. Results of the power consumed by individual devices while transmitting the beacon frame, averaged over 10 frames, are presented in fig. 2.

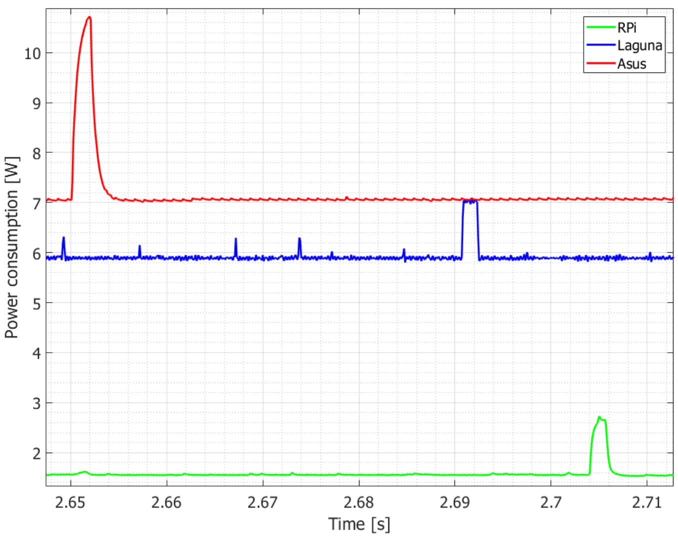

Fig. 2 Power consumption levels during the beacon frame transmission (EIRP 20dBm)

The beacon frames are broadcast regularly, every 100 ms by default, with a single beacon frame transmit time TBTT (*Target Beacon Transmission Time*) of 1024 µs, i.e. close to 1 ms. In the case of Raspberry Pi3 and Gateworks Laguna, an increased current consumption lasted for about 2 milliseconds, whereas with Asus it lasted for 2.5 ms. The rising edge was assumed as the beginning of the frame transmission whereas its end was marked by the moment when the falling edge levelled off and stabilized [7], [8]. It is immediately noticed that the devices augment their power demand for time intervals twice wider than those defined in their technical specifications, which can be attributed to the fact that the frame, prior to its transmission, must first be prepared and generated, which calls for computational power.

TABLE I
A POWER CONSUMPTION INCREASE – THE BEACON FRAME TRANSMISSION

Device (EIRP)	P_{max} [W]	P_{idle} [W]	Change [W]	Change [%]
ASUS (20 dBm)	7.14	10.88	3.74	52.44
ASUS (17 dBm)	7.15	11.05	3.90	54.63
ASUS (0 dBm)	7.20	11.20	4.00	55.66
	5.97	7.16	1.19	19.89
LAGUNA (20 dBm)				
LAGUNA (17 dBm)	5.98	6.91	0.93	15.56
LAGUNA (0 dBm)	5.99	6.63	0.64	10.62
	1.59	2.75	1.16	72.78
RPi (20 dBm)				
RPi (17 dBm)	1.59	2.65	1.06	66.87
RPi (0 dBm)	1.59	2.48	0.89	56.02

In order to determine the consumed power increase during a single frame transmission, the maximum power was read and compared with the average power level obtained during a transmission-free period, whereupon a difference between these two was calculated and outcomes presented in Table I. The greatest absolute power increase was measured with the Asus router, whereas the greatest relative growth was observed with the Raspberry. It is worth noticing that the former takes in the greatest amount of energy during the idle state; fourfold the energy consumed in this state by the Raspberry. Quite interestingly, decreasing EIRP causes the power consumed by this device (Asus) to grow, that appears illogical, even unreasonable, especially in the light of the other two devices lowering their energy consumption in response to decreasing EIRP. An obvious question to answer therefore was whether EIRP was indeed being decreased. The authors, after verifying the radiated signal with the use of a spectrum analyzer, confirmed that the EIRP was being altered accordingly to the GUI (*Graphical User Interface*) settings. An open question thus remains, why the power intake grows.

A supplemental experiment was also carried out to verify the influence of the SSID (*Service Set ID*) length, broadcast in the beacon frame, on the power intake, which concluded – in full accordance to expectations – with no noticeable effect.

III. A CHANGE OF THE BEACON INTERFRAME INTERVAL

In another experiment the influence was measured of the beacon frames transmission rate on the power consumed from its supply by the access point. Theoretically, decreasing this interval (i.e. increasing the rate) causes the network to converge faster, though on the other hand leads to the increase in the NIC power consumption [10]. In addition to that, a simulation of the tested devices lifetime was performed assuming a battery capacity of 20 Wh. The profile of the power intake changes during transmission of the beacon frames every 100 ms and 900 ms, respectively, as presented in fig. 3 and fig. 4.

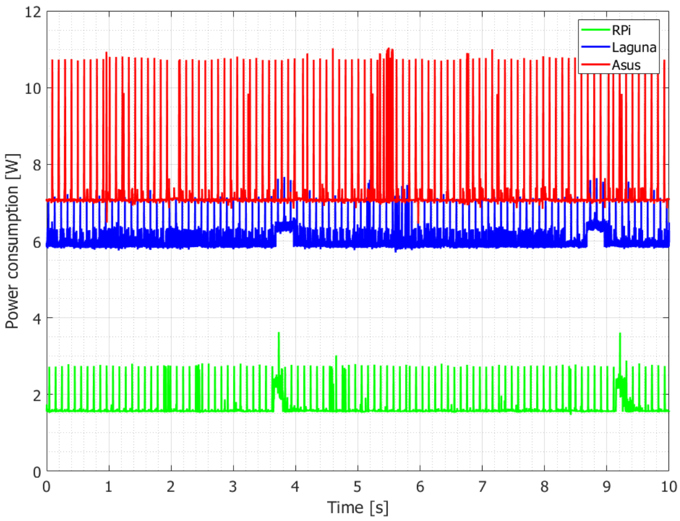

Fig. 3 The power consumption – a beacon frame sent every 100 ms (EIRP 20dBm)

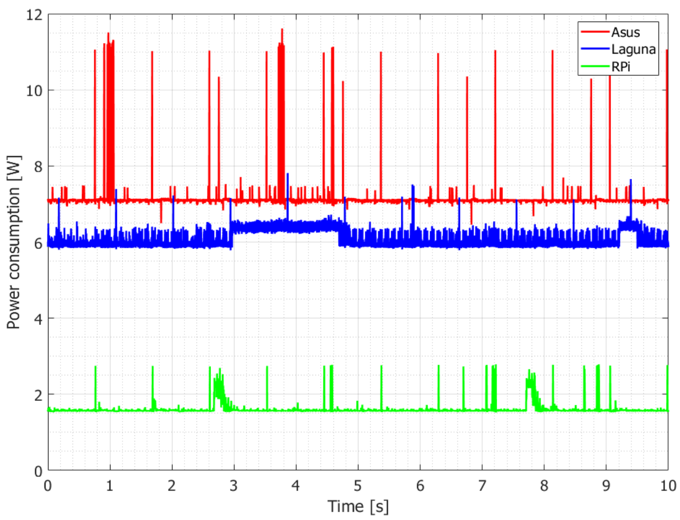

Fig. 4 The power consumption – a beacon frame sent every 900 ms (EIRP 20dBm)

In the figures one can notice instantaneous energy consumption peaks unrelated to the transmission of beacon frames, beyond the authors' control. These peaks are attributed to some processes occurring in the devices' operating systems and will not be analyzed herein. Similar investigations were carried out for the remaining rates of beacon frame broadcasts, with the interframe interval altered at 200 ms steps up to 900 ms. During measurements, no NIC's were connected to any of the access points. Based on the recorded 10-second long runs, average values of the consumed power were calculated for all of the tested intervals. The average lifetime values for: Asus, Gateworks and Raspberry, eventually: equaled 14, 17 and 63 hours, respectively. Detailed information is presented in Table II, Table III and Table IV.

TABLE II
MEASUREMENT RESULTS FOR THE VARIABLE BEACON TRANSMISSION RATE – ASUS ACCESS POINT

EIRP [dBm]	Beacon [ms]	Current [A]	Estimated lifetime [h]	Change [%]
20	100	1.431	13.97	-
	300	1.430	13.99	0.10
	500	1.427	14.02	0.32
	700	1.426	14.02	0.36
	900	1.422	14.06	0.64
17	100	1.434	13.95	-
	300	1.434	13.95	0.04
	500	1.428	14.01	0.45
	700	1.426	14.03	0.60
	900	1.425	14.03	0.63
0	100	1.455	13.75	-
	300	1.439	13.90	1.09
	500	1.438	13.90	1.13
	700	1.432	13.97	1.60
	900	1.431	13.97	1.64

Data presented in the tables were obtained after some post-processing. The third column contains instantaneous current consumed during the beacon frame transmission, later referenced to the averaged current in the idle mode (i.e. when no transmission takes place). Any values related to background processes were removed as well. In order to determine the influence of changes in the beacon interframe interval on the lifetime, a statistical number of frames broadcast during one reference second was found and next the average current in that second was found. A reference time for a frame transmission was set to be 2 milliseconds. The percentage results in the tables refer to the default rate of beacon frames emission, i.e. 100 ms. As could be expected, experimental outcomes confirm that as the interframe interval grows the demand for energy decreases.

TABLE III
MEASUREMENT RESULTS FOR THE VARIABLE BEACON TRANSMISSION RATE – LAGUNA ACCESS POINT

EIRP [dBm]	Beacon [ms]	Current [A]	Estimated lifetime [h]	Change [%]
20	100	1.206	16.58	-
	300	1.193	16.77	1.09
	500	1.192	16.78	1.13
	700	1.191	16.79	1.60
	900	1.190	16.81	1.64
17	100	1.206	16.58	-
	300	1.197	16.71	1.14
	500	1.196	16.72	1.19
	700	1.192	16.78	1.25
	900	1.188	16.83	1.40
0	100	1.207	16.57	-
	300	1.205	16.59	0.76
	500	1.195	16.74	0.83
	700	1.193	16.76	1.16
	900	1.193	16.76	1.49

It is worth noticing the scale of saving since calculations indicate that while the beacon frame rate decreases the devices lifetime prolongs, however by not more than 2% at best, a result achieved with the use of the Raspberry Pi3 platform for the interframe interval equal to 900 ms. Such a setting forced in an access point can, however, cause problems with detecting a network SSID that is broadcast in the beacons. This small influence on the power intake is caused by a relatively short duration of the beacon frame compared to the device total working time. A quick calculation corroborates the measurement-based outcomes. If the frame transmit time lasts 2 ms and the interframe interval lasts 100 ms then the resultant duty cycle is 2% meaning that only in 2% of the observed time the power demand is increased.

One more aspect to be discussed is the absolute difference in the energy consumption in the idle mode and during the transmission. As turns out, the attained energy saving is even smaller than previously. In addition to that, measurements have shown that the influence of a given parameter may be masked by other system processes. Measurements were performed for the values up to 900 ms although most access points allow for setting greater values. For example, this range in Asus devices usually spans between 20 and 1000 ms, in Netgear devices between 1 and 65535 ms and in D-LINK between 25 and 500 ms [11]. During the experiments it became evident that some NIC's were not able to connect to the access point when the beacon interframe interval was greater than 900 ms, which phenomenon requires further analysis but extends beyond the scope of this paper.

TABLE IV
MEASUREMENT RESULTS FOR THE VARIABLE BEACON TRANSMISSION RATE – RPI ACCESS POINT

EIRP [dBm]	Beacon [ms]	Current [A]	Estimated lifetime [h]	Change [%]
	100	0.321	62.36	-
	300	0.319	62.77	0.67
20	500	0.318	62.97	0.98
	700	0.318	62.98	1.00
	900	0.317	63.06	1.12
	100	0.318	62.87	-
17	300	0.318	62.89	0.03
	500	0.318	62.96	0.14
	700	0.317	63.03	0.26
	900	0.317	63.11	0.38
	100	0.322	62.20	-
	300	0.317	63.03	1.33
0	500	0.317	63.05	1.35
	700	0.317	63.11	1.45
	900	0.317	63.18	1.57

IV. ASSOCIATING A NIC TO A WIRELESS NETWORK

During making a connection between an access point and a NIC, synchronization and authorization data is being exchanged, which results in increased power consumption from the supply. The energy intake profile recorded upon joining a new user to the networks is presented in fig. 5 for all tested devices. It is fairly easy to notice that each access point increases its demand for power supply. As a part of the analysis a comparison was made between the average consumed power while joining (associating) a client to the network with the power taken in the idle state (Table V). The second column contains the averaged consumed energy during the association of a new client with the network. The practical experiment was carried for the beacon interframe interval of 100 ms.

The greatest "energetic effort" was made by the access point built on the basis of the Raspberry Pi3 platform. It may be so owing to the fact that NIC used was integrated with the board which made most of the operations related to the handling of NIC be performed by the processor, as opposed to other two access points. It is also worth noticing that the effect of joining a new client had a negligible effect on Laguna's outcomes whereas the influence of decreasing EIRP was as expected in the sense that it was followed by lightening the "energetic burden" of the device.

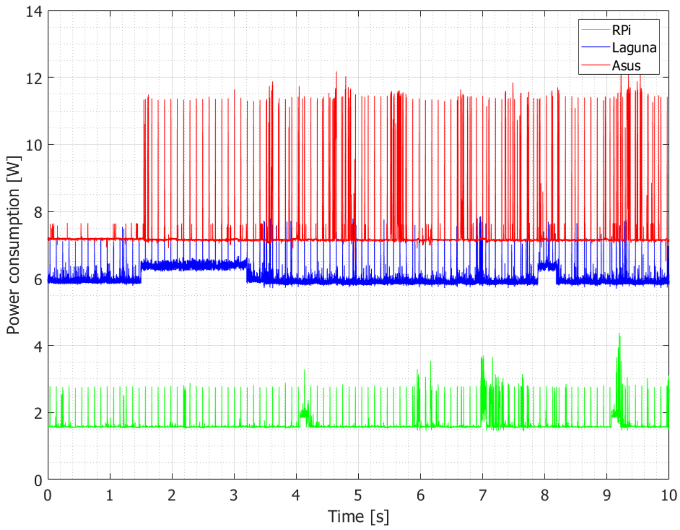

Fig. 5 The power consumption while associating a new client to the network

TABLE V
ENERGY CONSUMPTION WHILE JOINING A NEW CLIENT

Device (EIRP)	P_{join} [W]	P_{idle} [W]	Change [W]	Change [%]
ASUS (20 dBm)	7.37	7.14	0.24	3.31
ASUS (17 dBm)	7.37	7.15	0.22	3.09
ASUS (0 dBm)	7.35	7.20	0.16	2.20
	6.03	5.97	0.05	0.89
LAGUNA (20 dBm)				
LAGUNA (17 dBm)	6.02	5.98	0.05	0.75
LAGUNA (0 dBm)	5.99	5.99	0.00	0.02
	1.67	1.59	0.08	5.06
RPi (20 dBm)				
RPi (17 dBm)	1.65	1.59	0.07	4.18
RPi (0 dBm)	1.62	1.59	0.03	2.15

V. DATA TRANSMISSION

The last of the performed tests was aimed at determining the UDP data transmission influence on increasing the energy consumption and shortening the battery lifetime, with all measurements done with the use of *iperf* [12]. In each of the tested cases a maximum data rate mode was activated, depending on the modulation-coding schemes available with a particular access point. The TP-LINK T4UH card (MIMO 2x2; 300Mbps) was used as the receiver in the measurement system.

The impact of several WLAN receivers on energy consumption has not been considered. Devices were located at a distance of 3m. The observation of the registered energy consumption by all devices shown in fig. 6 indicates its remarkable surge during the data transmission in the network. It dominates to the point that makes it impossible to distinguish moments of the beacon frame emission.

The power intake during the experiment was referenced to the values measured in the device idle mode. It allows to estimate the degree to which the commence of data transmission by client devices shortens the lifetime of the tested equipment. Detailed calculation outcomes are presented in Table VI and Table VII ('Tx' denoting 'transmission').

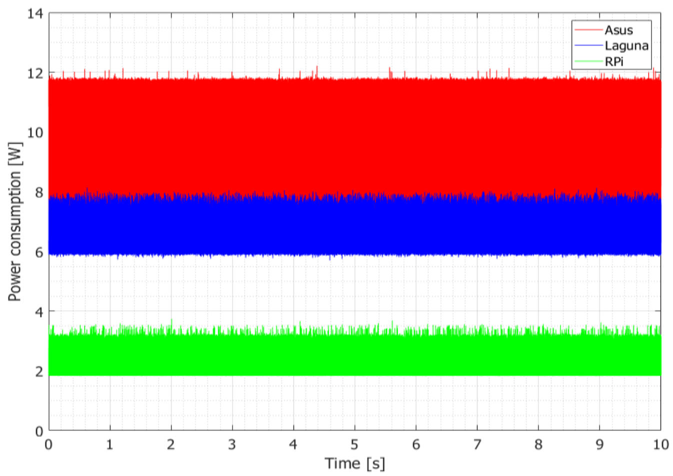

Fig. 6 Energy consumption during data transmission

TABLE VI
ENERGY CONSUMPTION DURING USER DATA TRANSMISSION

Device (EIRP)	P_{max} [W]	P_{idle} [W]	Change [W]	Change [%]
ASUS (20 dBm)	9.97	7.14	2.84	39.76
ASUS (17 dBm)	9.78	7.15	2.64	36.93
ASUS (0 dBm)	9.88	7.20	2.68	37.31
	6.63	5.97	0.66	11.00
LAGUNA (20 dBm)				
LAGUNA (17 dBm)	6.50	5.98	0.52	8.65
LAGUNA (0 dBm)	6.42	5.99	0.43	7.20
	2.00	1.59	0.41	25.68
RPi (20 dBm)				
RPi (17 dBm)	1.96	1.59	0.37	23.13
RPi (0 dBm)	1.94	1.59	0.35	21.76

Similarly to the case of joining a new client to the network, the lowest sensitivity was observed with Laguna device. In this case the demand for energy was the smallest and equaled on the average c.a. 10 percent. On the other hand, the energy demand with Asus device increased by c.a. 40% on average, which is a rather high value. In the midst of these figures is Raspberry with its 25% average rise.

These values have their obvious bearing on the battery lifetime. Magnitudes in Table VII were calculated assuming a hypothetical 20 Wh battery, as before. The smallest simulated lifetime shortening is thus expected to take place with Laguna, i.e. about 10%. The second in the rank is Raspberry with c.a. 25% while the last position is taken by Asus yielding about 30 percent.

The second and the third column contains interesting absolute values, wherein Raspberry appears to be an undisputed winner in the battery lifetime competition, by achieving 60 hours of lifetime in the idle mode and 50 hours in the transmission ('Tx') mode, leaving the other two devices far behind.

TABLE VII
THE BATTERY LIFETIME DURING USER DATA TRANSMISSION

Device (EIRP)	Estimated battery lifetime (idle) [h]	Estimated battery lifetime (Tx) [h]	Change [h]	Change [%]
ASUS (20 dBm)	14.01	10.03	-3.99	-28.45
ASUS (17 dBm)	13.99	10.22	-3.77	-26.97
ASUS (0 dBm)	13.90	10.12	-3.78	-27.17
	16.74	15.09	-1.66	-9.91
LAGUNA (20 dBm)				
LAGUNA (17 dBm)	16.72	15.39	-1.33	-7.96
LAGUNA (0 dBm)	16.69	15.56	-1.12	-6.72
	62.83	49.99	-12.84	-20.43
RPi (20 dBm)				
RPi (17 dBm)	62.97	51.14	-11.83	-18.79
RPi (0 dBm)	62.91	51.67	-11.24	-17.87

In evaluating the transmission mode one should not only consider the power consumption but also the offered efficiency, keeping in mind that a user's comfort and satisfaction with the device performance (in terms of data rate) is a priority in WLAN systems. Hence, in the three following figures (fig. 7, fig. 8, fig. 9), 10-seconds long fragments of the throughput measurements were presented, obtained with the use of the aforementioned *iperf* software.

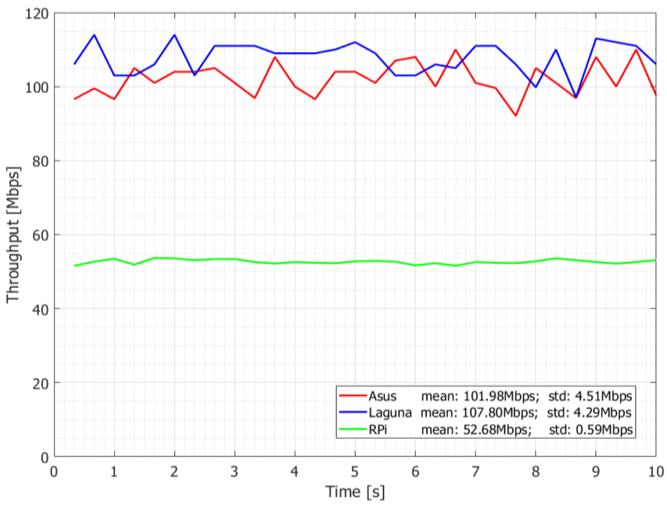

Fig. 7 Throughput measurements with EIRP of 20 dBm

Each EIRP case measurement consisted of three 60-seconds long sessions, presented in the figures along with the average throughput along with its standard deviation (σ) for demonstrating the transmission stability. The obtained results indicate that similar performance was attained for Laguna and Asus, circulating around 100 Mb/s but with clearly increasing standard deviation in response to decreasing EIRP. An exception from this rule can be observed for Raspberry, which is characterized by a remarkably low σ and a twice lower efficiency than the other two access points.

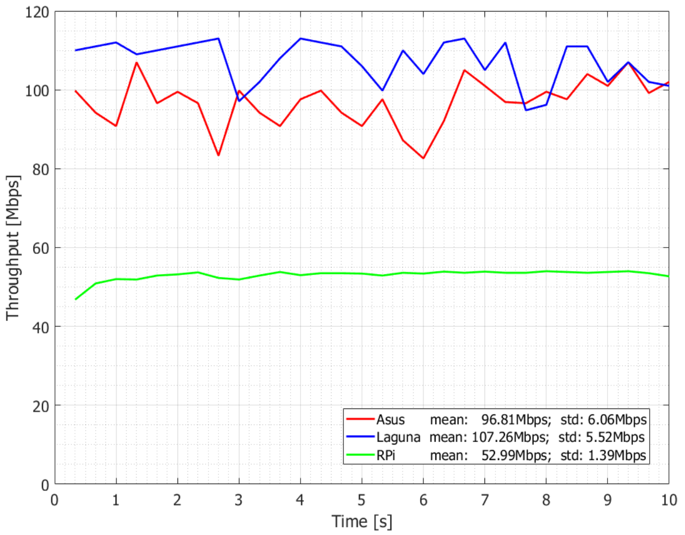

Fig. 8 Throughput measurements with EIRP of 17 dBm

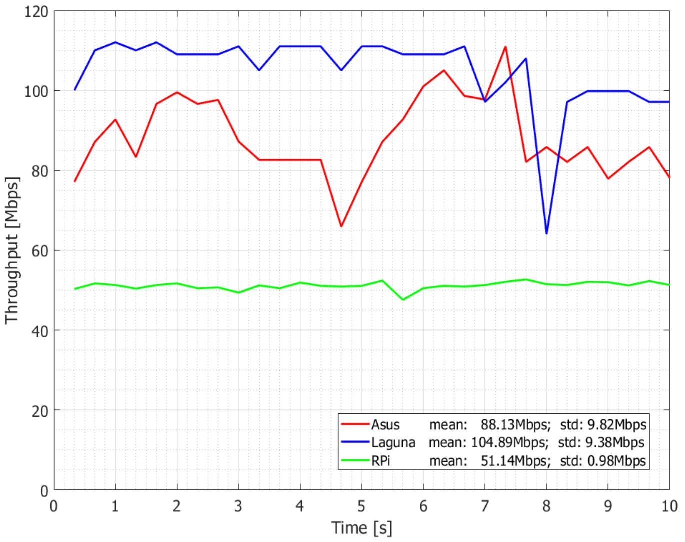

Fig. 9 Throughput measurements with EIRP of 0 dBm

Conclusion

The scope of work presented herein encompassed the energy consumed wireless WLAN access points working in the IEEE 802.11n standard. Each of the examined devices was representative of a different group of devices commonly available in the market, that can be used to build a wireless computer network.

An analysis of the measured energy consumption results as a function of decreasing beacon frames transmission rate leads to a conclusion that the variation of the beacon interframe interval has no significant effect on the energy intake. In fact, an instantaneous current surge appears upon the beacon transmission, but because of the short frame length its total influence is negligible. The measurement outcomes indicate a clear trend in the lifetime extension with extending intervals between beacons, proving however that the energy savings as well as the ensuing battery work time extension, are insignificant. Moreover, considerable increase in the *beacon* interframe interval may cause substantial issues while joining new devices to the network.

The scope of investigations embraced two other phases, important in the view of a wireless network operation, such as the new user association (joining) and the data transmission. It turns out that the former proves to be less energy-costly than the latter. The increase in the energy consumption with Laguna was negligibly low whereas with two other access points it increased by a few percent.

In diagrams presented in chapter V one can observe that the Raspberry Pi3 device offers a twice lower, yet very stable in terms of variation, throughput. This evident deterioration in throughput stems from the fact that the WLAN NIC in Raspberry Pi3 does not support MIMO. With the maximum data rate of 72.2 Mbps at the physical layer, the value of 50 Mb/s obtained at the application layer therefore appears to be more than satisfactory.

The experiments and analyses demonstrate how crucial a task it is to properly match access points to the network requirements. If a large traffic and high required efficiency is anticipated in the network, one should consider choosing more advanced hardware solutions, such as Asus or Laguna. If, however, a designed network is intended for the Internet of Things traffic with a major requirement for an energy-efficient media gateway, the Raspberry Pi3 platform may be a reasonable choice. The offered transmission efficiency is sufficient for most SOHO applications while outperforming the other two competitors. On top of that, the power consumed by Raspberry Pi3 can be further decreased by deactivating unnecessary peripherals [9].

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