Experimental Evaluation of Alkaline Batteries's Capacity for Low Power Consuming Applications

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***Abstract*—The technology advances over the recent years brought on market many portable consumer and telecommunication electronic devices, most of which utilize low-power embedded systems. Significant part of these devices is nowadays supplied from the primary batteries, among which the alkaline ones are the most widespread. The paper presents the real-life discharge curves and measurement results of available energy for various commercially available off-the-shelf alkaline batteries under continues and intermittent discharge. The specifics of the paper is that it focuses the battery discharge profiles, which are typical for the portable devices based on low-power microcontrollers in general and Wireless Sensor Network (WSN) nodes in particular. Therefore, provided in the paper data is valuable both for engineers for estimating their devices' lifetimes and for researchers for evaluating battery models or estimating performance for energy efficiency improvement mechanisms. Besides, the presented results reveal importance of battery characteristics consideration for lifetime improvement and demonstrate need for energy-source aware optimization algorithms for battery supplied systems in general and for WSN especially.**

***Keywords*-WSN; embedded systems; primary alkaline battery; lifetime; capacity;**

I. Introduction

The technology advances of the recent years brought on market many novel portable consumer electronic devices, including multiple portable communication devices, computers and medical devices [1]. Despite numerous differences between all these devices, they all require small and efficient sources of electrical energy for their operation. Although recently there have been suggested numerous technologies for scavenging the energy from different environment sources, wide utilization of these technologies is still very limited due to current state of technology and specific application's requirements. Therefore batteries remain nowadays the most widely used sources of power for various portable devices. So, according to [2] the battery market in 2012 only in US will exceed $16.4 billion and will be over $50 billion worldwide [1].

The consumer device operation time using specified source of energy (i.e. "system lifetime") is one of the most important parameters for any portable device, for defining and optimizing which the information about source of energy characteristics is essential. Although some of the information about the Commercially available Off-The-Shelf (COTS) batteries can be obtained from their data sheets or handbooks (e.g. [3], [4]) but there one will usually find only the nominal battery capacity. This nominal capacity is measured under specific environment conditions and load profile, which mostly often differs from real-life profiles of portable devices that are build around low-power embedded systems (e.g. nominal capacity of AAA batteries is often defined under 10 times higher discharge current, than the maximum one in Wireless Sensor Network's (WSN) nodes). Meanwhile, in the major part of the existing research works, authors are focusing on the influence of several load profile parameters on COTS battery's capacity for particular type of batteries. So, in [5] authors showed how capacity of a single lithium coin cell battery is affected by the load profile. In [6] the authors measured energy available from coin-sized battery versus average discharge current and provided the mechanism for embedded system operation optimization for WSN node lifetime maximization. In [7] was explored the recovery and rate capacity effects for the batteries using 1.2 Volt AAA nickelmetal hydride battery as a reference. Although these works provide valuable references for using particular battery for particular applications, they do not provide the full picture. Besides, although today there exist numerous different models for battery behavior modeling (e.g. see [8]), for most of these models it is very complicated to find actual parameters that would allow to simulate particular battery type and its behavior in particular system.

Therefore, in the current paper we provide the available energy values and discharge curves for *different discharge profiles* of *the various real-life COTS primary alkaline batteries*, that are nowadays the most widely used type of primary batteries and represent over 60% of the primary battery market [1], [2]. The current work is intended to provide a reference, which can be used both by engineers for estimating their portable telecommunication devices' lifetime and by researchers for evaluating battery models or estimating performance of energy efficiency improvement mechanisms using real-life data.

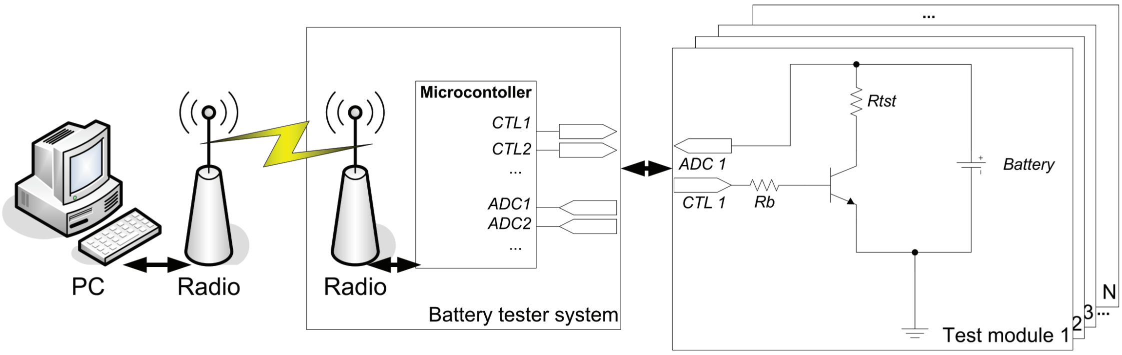


Figure 1: The experiment set-up

II. Experiment Setup

For measuring the battery energy we have used the testbed, presented on Fig.1. The testbed is implemented using Texas Instruments (TI) eZ430-RF2500 development boards [9]. The MSP430F2274 microcontroller [10] of the board implements both load connection control (using CTL lines the microcontroller can connect (CTL high) or disconnect (CTL low) the load from each tested battery) and battery voltage measurements (the ADC lines are connected to microcontroller's inbuilt 10-bit analog to digital (A/D) converter with internal 1.5 V source as reference). The developed testbed during the tests was used to control simultaneously up to 5 different testing modules, each working with a separate battery. Each battery test module (see Fig.1) can emulate different battery discharge load (through using required $Rtst$ resistor) and different discharge profile (through specifying the period and duty cycle of CTL signal). The specified discharge profile is implemented using inbuilt microcontroller's timers and clock crystal. Besides, the microcontroller clocks and timers are used to periodically launch the measurements of each battery voltage and to track time from the start of experiment. The measurements for each testing module's battery voltage level are done approximately every 10 seconds with the batteries disconnected from the load. If during a measurement it is detected, that one of the predefined voltage threshold for some battery has been overcome, the time mark is written to microcontroller's Flash memory. To reduce the error for time measurement due to microcontroller's clocks instability, obtained during the tests time stamps have been later calibrated using external time reference. When required, the measurement data in microcontroller Flash memory can be accessed from a PC over wireless channel that is implemented using CC2500 radio chip [11] of the testbed board.

The measurements were conducted for 6 different types of COTS alkaline primary batteries, that are nowadays the most widely used type of primary batteries [1]. The nominal parameters of the tested batteries are presented in Table I. The measurements were made for discharge currents of 2-

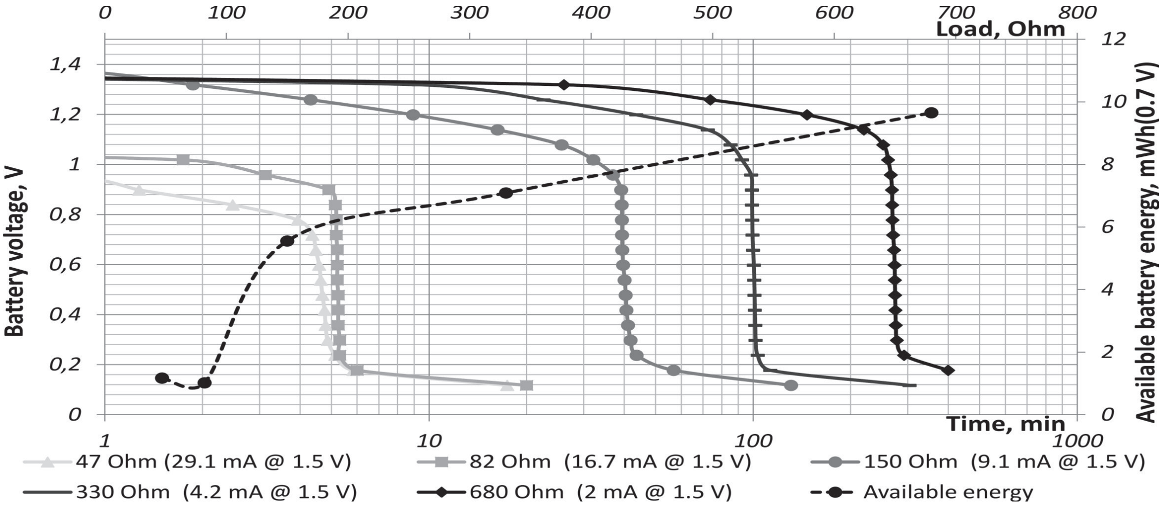
Table I: Nominal tested batteries' parameters (data from the manufacturer)

Battery type (IEC/AG)	Dimensions (mm) diameter x height	Nominal capacity, mAh	Nominal voltage, V
LR03/AAA	10.5 x 44.5	1000	1.5
LR44/AG13	11.6 x 5.4	138	1.5
LR1130/AG10	11.6 x 3.1	80	1.5
LR41/AG3	7.9 x 3.6	28	1.5
LR626/AG4	6.8 x 2.6	18	1.5
LR621/AG1	6.8 x 2.1	13	1.5

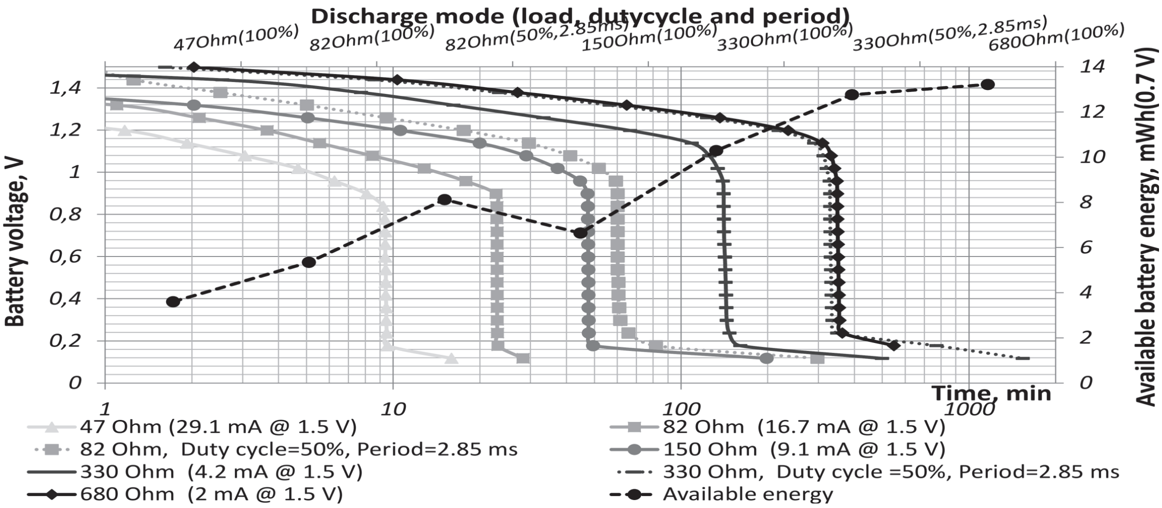
Table II: Typical current consumption for WSN nodes [13]

Operation	WSN nodes		
	Telos	Mica2	MicaZ
Node standby	5.1μA	19μA	27μA
Microcontroller (MCU) idle	54.4μA	3.2mA	3.2mA
MCU active	1.8mA	8mA	8mA
MCU active + Radio RX	21.8mA	15.1mA	23.3mA
MCU active + Radio TX	19.5mA	25.4mA	21mA
MCU active + Flash read	4.1mA	9.4mA	9.4mA
MCU active + Flash write	15.1mA	21.6mA	21.6mA

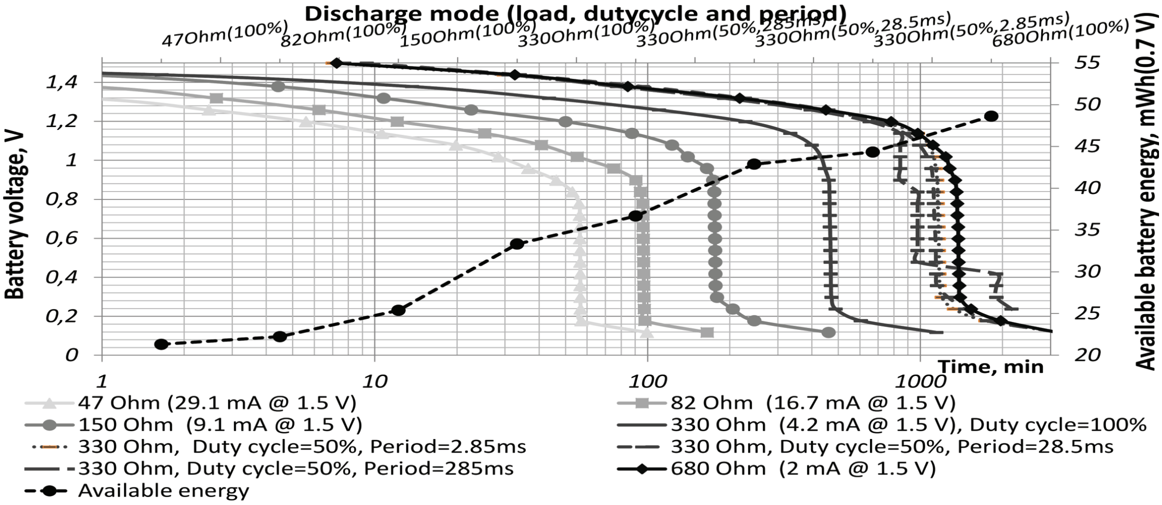
30 mA that are typical for low power devices based on the embedded systems in general and for Wireless Sensor Network (WSN) nodes in particular (e.g. see Table II). For obtaining required discharge current level were used $Rtst$ resistors with 2% tolerance. The maximum cumulative error for obtained results due to the $Rtst$ tolerance, errors for A/D conversion and clock instability is estimated to be less than 5%. As can be seen from Fig.1, the testing modules do not have any current stabilization system, thus the actual battery discharge current decreases along with battery voltage through out battery discharge. This is done intentionally, as significant part of existing embedded systems based portable devices, and especially the ones utilizing low duty cycle operation as e.g. WSN nodes, do not have supply voltage stabilizing circuits and their actual current consumption decreases with supply voltage decrease (e.g. see [12]).



(a) AG1 battery under continuous discharge

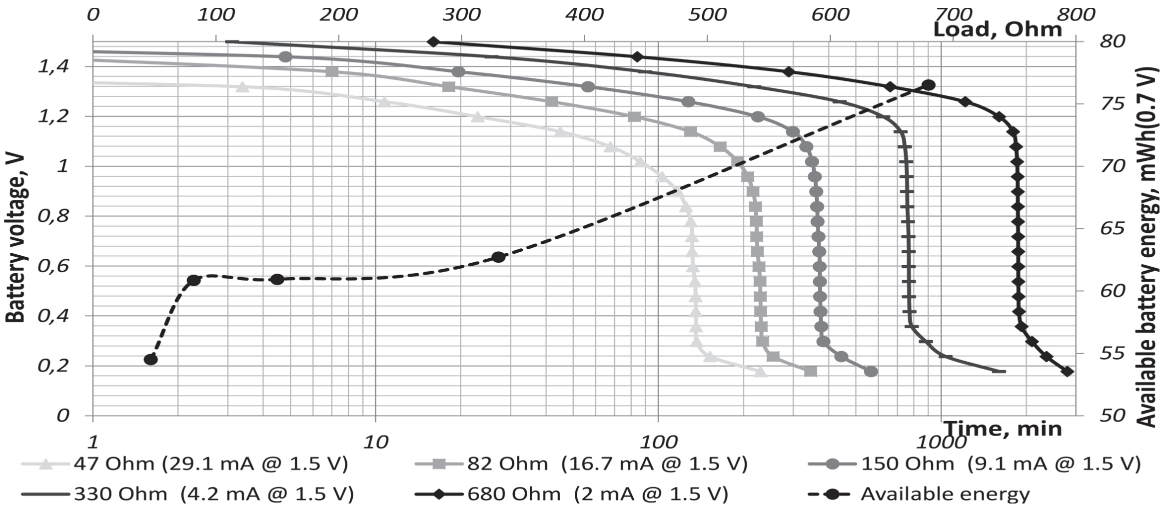


(b) AG4 battery under continuous and intermittent discharge

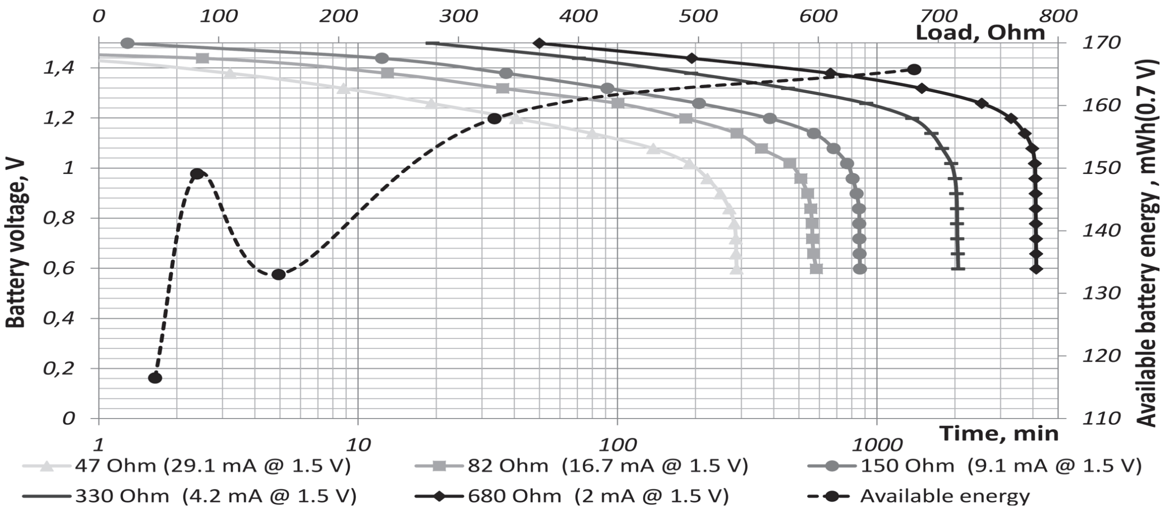


(c) AG3 battery under continuous and intermittent discharge

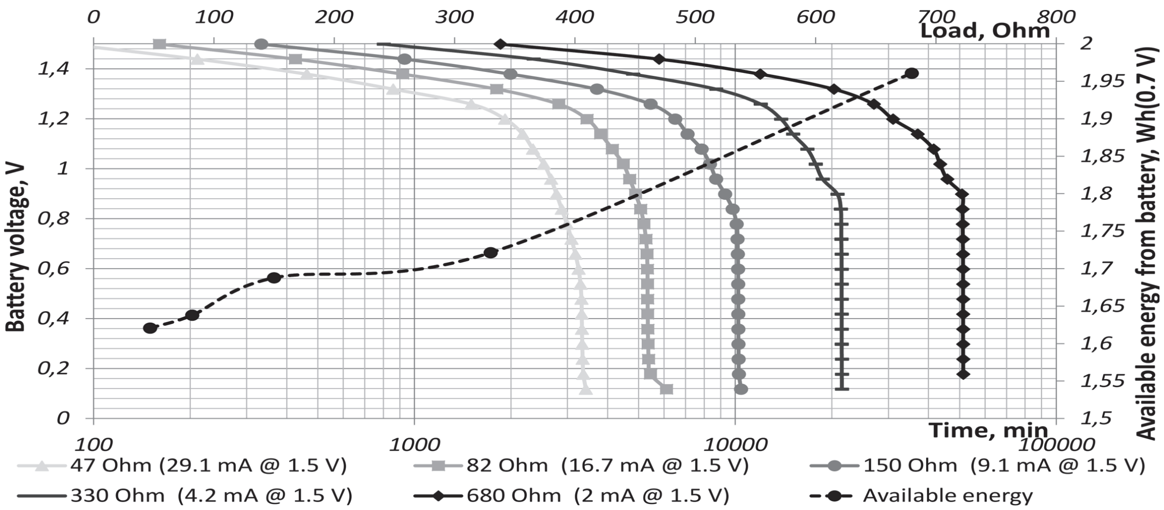
Figure 2: Battery discharge and available energy curves for COTS alkaline batteries



(d) AG10 battery under continuous discharge

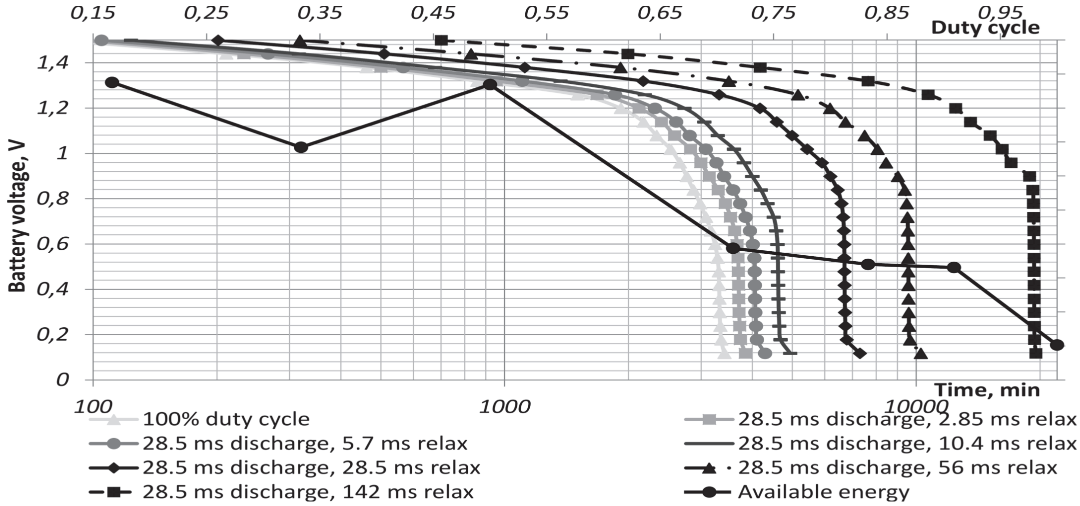


(e) AG13 battery under continuous discharge

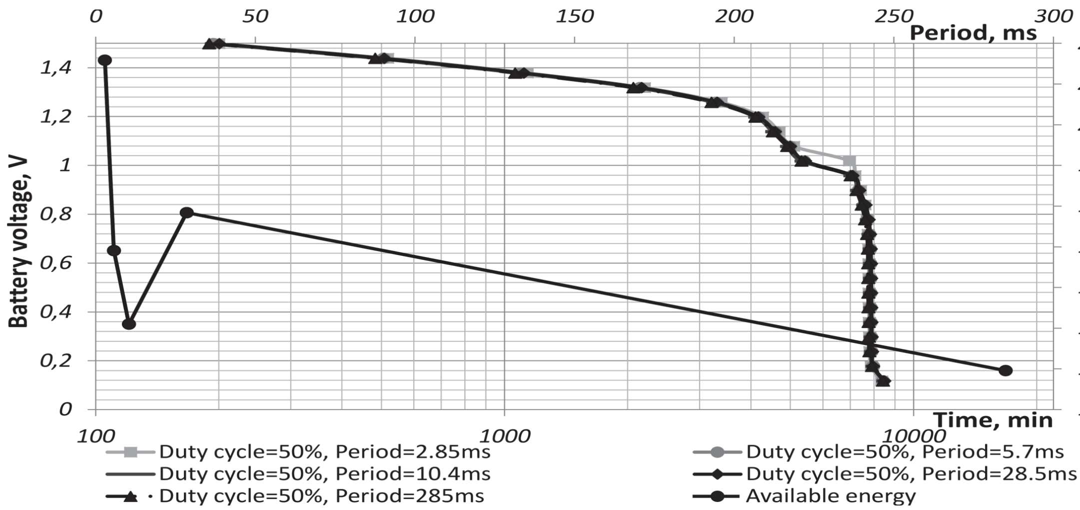


(f) AAA battery under continuous discharge

Figure 2: Battery discharge and available energy curves for COTS alkaline batteries (cont-d)



(g) AAA battery under intermittent discharge (Load=47Ohm), effect of relaxation



(h) AAA battery under intermittent discharge (Duty cycle=50%, Load=47Ohm), effect of period

Figure 2: Battery discharge and available energy curves for COTS alkaline batteries (cont-d)

III. Results

The measurements results, showing discharge curves and available energy of tested batteries are presented in Figs. 2a-2h. Figs. 2a-2f present the curves obtained for the case, when load has been connected to tested batteries permanently (i.e. under continuous discharge - the CTL lines are driven high during discharge), while Figs. 2g-2h together with some curves in Figs. 2c and 2b present results for the case when during discharge the load has been periodically connected to and disconnected from batteries (i.e. under intermittent discharge - CTL periodically switched between high and low). The available battery energy that is presented on charts has been calculated using piecewise-linear approximation for current and voltage values between neighboring thresholds bypasses and estimates the energy, one can get from a battery before its voltage gets below 0.7 Volts (1.4-1.5 V is a typical threshold voltage required to start most often-used microcontrollers [12]).

As reveal the presented curves, provided by manufacturer nominal battery capacity values differ significantly from results of measurements (see Table I): e.g. if for AG1 batteries with 680 Ohm load it is possible to get 9.65 mWh (while nominal is 19.5 mWh), for AAA battery and the same load the battery energy exceeds 1.95 Wh (with nominal 1.5 Wh). Besides, the battery energy strongly depend on the load. So, for small sized button batteries with low capacity the difference between the energy available for minimum (47 Ohm) and maximum (680 Ohm) loads is reaching 8 times (see e.g. AG1). For batteries with higher capacitance this difference decreases and for AAA batteries reaches only

20%. As reveal Figs. 2b, 2c and 2g during intermittent discharge the energy that can be obtained from battery is higher than during continues discharge with the same load. This is happing due to battery relaxation effect [14], [15]. As revealed in presented figures, the relaxation effect for small sized bateries is expressed more clearly: 50% duty cycle for AG4 batteries for 82 Ohm load allows to increase avilable energy for 50%, while for AAA battery 50% duty cycle provides only 20% available energy increase. Besides, as can be noted from Fig. 2g, "relaxation" time increase for battery under intermittent discharge allows to increase the available battery energy. Also, as possible to assume from Fig. 2h, higher periods with same duty cycle reduces the available from the battery energy, although further experiments are required to prove it.

As can be noted from presented figures, some measurements results (e.g. available energy for AG1 battery and AG13 battery with 82 Ohm load, available energy for AAA battery with 50% duty cycle with 47 Ohm load) are breaking the trends. This can be effect of discussed in Section II measurement error sources and possible individual differences between the tested batteries (before tests the initial voltage for all the batteries was checked and were used only the batteries with initial voltage difference of less than 1%)

IV. Discussion and Conclusion

In the current paper we have presented and discussed the results of practical measurements of available energy from different types of the commercially available off-the-shelf alkaline batteries under continues and intermittent discharge. Unlike it is done in the most of existing research works and in data sheets from battery manufacturers, during our measurements we have tested the batteries under very low loads (having discharge current within 2 mA to 30 mA), which are typical for portable devices that are using low-power embedded systems and for Wireless Sensor Network nodes in particular. The presented in the paper results reveal the influence of different discharge profile parameters on available battery energy and provide valuable reference to real-life measurement data, that can be used both by engineers for estimating portable devices' lifetime and by researchers for evaluating battery models or estimating performance of energy efficiency improvement mechanisms.

As can be noted from the presented data, the energy available from a battery strongly depends on battery discharge current - the higher the discharge current is, the less energy it is possible to get from a battery. This effect should be especially considered for small-sized batteries with low capacity. Besides, the presented results reveal that under intermittent discharge a battery could provide more energy, than during continues discharge. This happens due to battery relaxation effect and, as can be seen from presented data, affects small-sized low-capacity batteries stronger, than bigger batteries with higher capacity. Besides, increase of relaxation period during battery intermittent discharge allows to increase the available battery energy. Also, basing on the presented data it is possible to expect, that the increase of period while keeping same duty cycle during battery intermittent discharge will cause the reduction of available battery energy, although further experiments are required to prove that.

Basing on the presented results, it becomes obvious that working mode parameters for battery-supplied portable device strongly influence available from battery energy and thus lifetime for whole device. This is especially important for devices, supplied by small-sized batteries with low capacity, for which the lower discharge currents can dramatically increase available from battery energy and thus overall device's lifetime. Therefore, the consideration of described batteries' features is *essential* for battery-supplied portable devices' lifetime improvement which requires *development of special algorithms for energy-source aware device operation optimization* for reaching the topical level of energy efficiency. This will be especially beneficial for such systems as Wireless Sensor Networks, which often have very limited resources and have various means for changing both single node and whole sensor network operation.

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