Optimization of Microcontroller Hardware Parameters for Wireless Sensor Network Node Power Consumption and Lifetime Improvement

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Abstract— **In this article the results for study of the influence of different microcontroller hardware parameters on the system overall power consumption and thus also on the system lifetime are presented. The influence of the supply voltage, clock frequency and emplacement of the program in the microcontroller memory for MSP430 microcontroller, which is often used nowadays in Wireless Sensor Networks (WSN) nodes, were evaluated. Additionally, we have studied the influence of different power supply systems for the node lifetime and figured out the optimal microcontroller working mode parameters, which allowed to maximize the amount of microcontroller operations for power supply charge using a normal battery and an energy harvesting system based on light energy harvesting. Although the motivation of this article has been the requirements of energy efficient WSN solutions obtained results are as well applicable to any microcontroller based embedded system that is working in harsh energy conditions.**

Keywords- energy efficiency; microcontroller; wireless sensor network

I. INTRODUCTION

Improvement of technologies over recent years has allowed the integration of high CPU performance and low power consumption in small sized casing – which is crucial especially for such systems as Wireless Sensor Networks (WSN). These latter technology developments allowed to broaden the range of applications for WSN and to develop new types of applications – the ones that do not require battery supply and are able to scavenge the energy from the environment. During recent years, numerous demonstrations have been presented which showed the possibility of collecting and utilizing the energy from different environment elements, like:

- Light [1,2,3,4]
- Temperature difference [1,3]
- Vibration [1,3,5]
- Water, air or gas flow [1,3,4]
- Electrical or magnetic fields [1,3,6].

The development of such technologies allows developing WSN nodes which can fulfill the tasks autonomously without human intervention for extremely long periods of time. Nevertheless such systems have some specialties and requirements that distinguish them from the other WSN systems. The main requirement is the minimization of the node power consumption as well from the protocol and software side and from the hardware side. Although different communication protocols and data processing algorithms, which aim to lower the node power consumption, have been presented and evaluated during recent years, the problem of influence of hardware parameters and choice of optimal hardware settings for WSN nodes still has many unstudied points.

An important contribution to the problem of microcontroller hardware parameter influence on node power consumption was made in [7] and [8]. In [7] were presented the results for study of microcontroller clock frequency influence on the node overall power consumption and it was figured out that microcontroller supply voltage has influence on the node power consumption. In [8] more detailed studies on the supply voltage influence on the power consumption of the node were reported and study for node lifetime evaluation using different microcontroller working modes for CR2450 battery was also included. The results in [8] showed that a microcontroller of WSN node has some optimal clock frequency and voltage settings that maximize the node lifetime (in the sense of the number of operations, conducted during the node lifetime) and this frequency usually differs from the frequency that minimizes the power consumption for single microcontroller operation and depends on the parameters of the used battery.

In this work, we study the influence of these and some other important parameters, like e.g. the program emplacement in microcontroller memory, on the node power consumption. The influence of node power consumption on the overall node lifetime for the cases when the system would be supplied using a battery and use energy scavenging from the light was also studied. We did not take into consideration the impact of possible peripheral components like sensors, analog to digital converters, external memory chips or wired communication interfaces on node power consumption, as the use of these components depends on application. Instead, we focused only on the influence of the components which are general for all WSN nodes like microcontroller, radio and power source.

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II. INFLUENCE OF MICROCONTROLLER PARAMETERS ON NODE POWER CONSUMPTION.

Today the most general WSN nodes usually have architecture similar to one presented in Fig. 1.

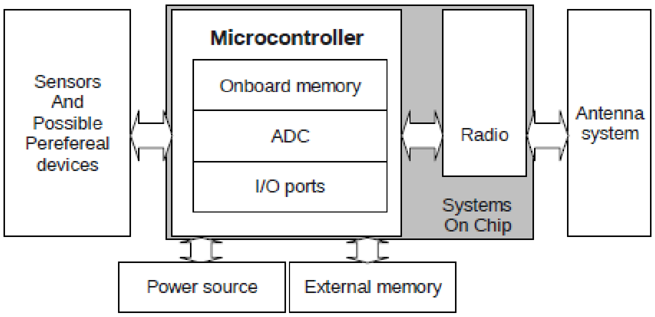

Figure 1. The typical structure of a WSN node

To save limited power resources, the microcontroller of WSN node stays for big amount of time in a low power mode, periodically switching to an active mode to read data from sensors or to communicate via radio. Accordingly, the lifetime of the node for the system without static power supply, would depend as well on the node overall power consumption and on power source discharge characteristics. The power consumption of a node is determined by the consumption of the microcontroller, radio and the peripheral devices for active and low-power sleep modes and on system scheduling.

Microcontroller in WSN node is the key component which controls all the work of peripherals and radio communication. Depending on application, WSN node is also often required to make some data processing before sending the data to the receiver. In several works (for example [9]) it has been shown that in many cases data processing on the node allows to reduce the amount of the information, which is required to be transmitted over WSN. This allows the improvement of the power consumption of the whole WSN as radio communication usually has higher power consumption than the data processing.

There are several parameters which define the power consumption of a single microcontroller and which could be chosen optimally to lower the power consumption of the whole system. The most important of them are: microcontroller clock frequency and supply voltage.

A. Microcontroller clock frequency

Microcontroller clock frequency defines the available processing power of the node. The clock frequency for microcontroller can be provided from different external clock crystals or from internal digital clock oscillator (DCO), which is a part of many contemporary microcontrollers, like Texas Instruments (TI) MSP430[10]. DCO provides a broad range of frequencies and allows to make fast (several clock cycles length) clock changes during runtime. Usage of DCO for getting the clock signal has one advantage which is crucial for WSN with low power consumption requirements – it does not require any external components, that allows to lower the power consumption, size and price of the node.

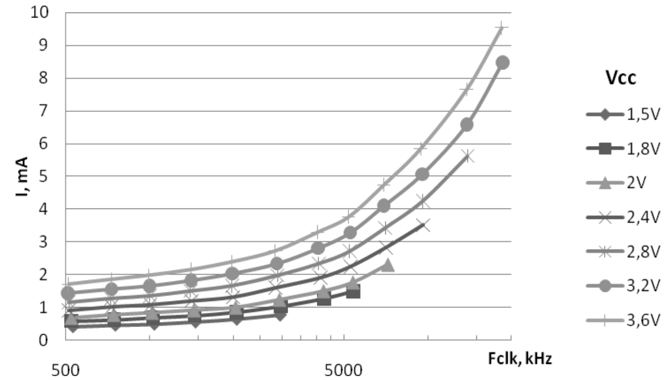

Figure 2. Current-frequency curves with microcontroller in active mode (Flash program)

During recent years, several works that involve studies of microcontroller clock frequency influence on node power consumption have been published [7,8,11]. Studies for previous versions of MSP430 microcontrollers were presented in [7] and it was pointed that the optimal frequency from the point of power consumption lays at frequency around half of the maximum possible frequency for microcontroller. Similar results were achieved in [8].

For our study, we have used TI eZ430-RF2500 boards [12], which encapsulate MSP430F2274 [13] microcontroller and CC2500 [14] radio chip. During microcontroller power consumption measurement, the radio chip was in sleep mode with the lowest power consumption of less than 1 μAh, all other peripheral devices were switched off and the microcontroller was nonstop running the test program. The resulting current-frequency curves are presented on Fig. 2.

Fig. 2 reveals that to get high clock frequencies it is required to have higher supply voltages and that the current consumption of microcontroller for using the same clock frequency strongly depends on supply voltage. So, for example the difference between the current consumption for working with 512 kHz clock frequency using 1.8 V and 3.6 V is around 3 times although the amount of made calculations remains almost the same. For higher clock frequencies, the rate between maximum and minimum consumed currents becomes lower (for 4 MHz, for example – it is around 2.5 times), but it is still significant for studying the possibility of using voltage control for lowering node consumption.

The main result, which can be seen from Fig. 2, is that the lowest current consumption for any particular clock frequency is achieved when the microcontroller is using the lowest possible supply voltage value for that particular frequency.

Although the dependence of the consumed current on used clock frequency is important for defining the lifetime of the node it does not fully describe the efficiency of energy usage. Power efficiency is calculated as the amount of consumed energy required per million instructions - mW/MIPS. Fig. 3 presents a 3D plot that summarizes dependence of power efficiency from supply voltage and clock frequency.

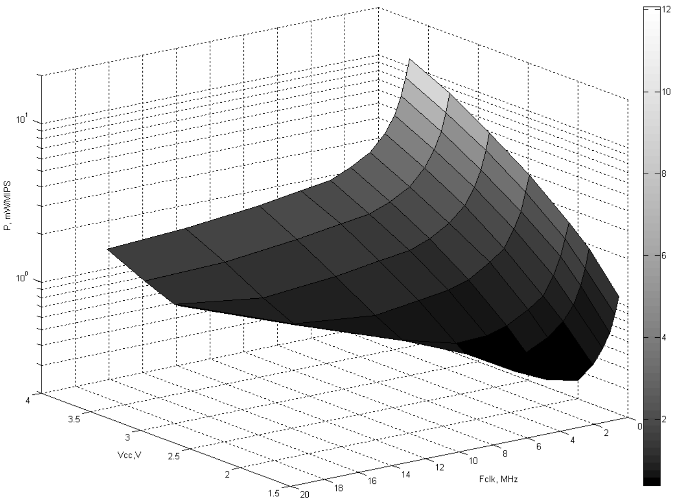

Figure 3. Dependence of microcontroller supply voltage and clock frequency on node power consumption during calculation (Flash program)

Fig. 3 shows that although the usage of low clock frequencies allows getting the lowest continuous current consumption, low clock frequencies are the most ineffective from the point of power usage. The reason for it is that usage of lower clock frequencies requires much longer data processing time than the modes with higher clock frequencies which demand higher supply current. There is a minimum corresponding to the most power efficient calculation mode. The absolute minimum is at around 5-6 MHz clock frequency, which is lower than the optimal frequency reported on [8]. The main reasons for this difference can be that in our tests we used different microcontroller family and that during our test we were not using any other peripheral components.

B. *Microcontroller supply voltage*

Above we have already pointed out that the maximum possible clock frequency for the microcontroller depends on available supply voltage. The exact values for defined minimal supply voltages for different frequencies and the dependence on current consumption from supply voltage are presented on Fig. 4.

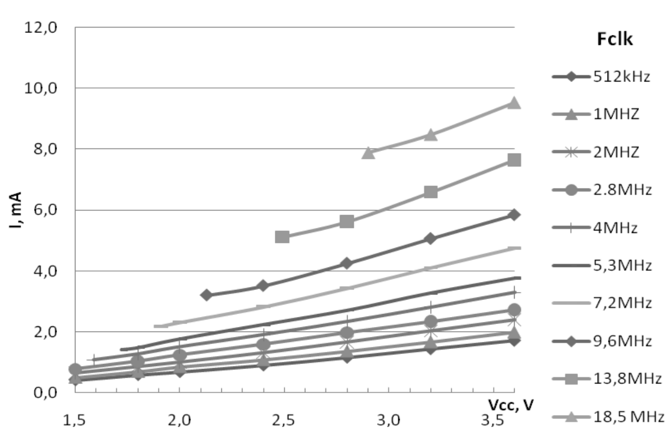

Figure 4. Current-voltage curves with microcontroller in an active mode

One interesting thing, which can be found from Fig. 4, is that the microcontroller can actually work from the voltage around 1.5 V which is below the value of 1.8 V marked in the datasheet [10]. In our testing program, we have implemented a simple control loop, which periodically launched a self-testing subroutine to detect possible calculation errors caused e.g. by the usage of too low supply voltage. According to our tests, the microcontroller running with voltages even below defined in datasheet 1.8 V was capable of passing the test calculations without errors.

Another thing that was discovered concerning microcontroller work with low supply voltage is that there present a hysteresis of switch-on and switch-off threshold voltages: the microcontroller using nominal clock frequency of 1 MHz switches on at the supply voltage of 1.5 V and switches off at voltage only around 1.38 V. The same behavior applies at higher frequencies – for each frequency there is a switch-on threshold (the voltage, which is required for starting working using a certain clock frequency) and a switch-off threshold (the voltage where the microcontroller is unable to continue to work using this frequency and reboots). Depending on the frequency, the switch-on threshold was found to lie from 0.12 V (for low clock frequencies) to 0.4 V (for high clock frequencies) above the corresponding switch-off threshold. For all curves, presented in the article the values are given to the switch-off threshold.

From presented results, it is possible to conclude that to get the minimum power consumption it is necessary first to switch to intended frequency using supply voltage higher than the switch-on threshold of this clock frequency and then to lower supply voltage to a value slightly above the switch-off threshold at that frequency.

During the study, it was also noticed that supply voltage influence is not limited only to the switch on/off point for the frequencies, but it also influences DCO clock frequency and its duty cycle. The corresponding experimental curves are presented on Fig. 5.

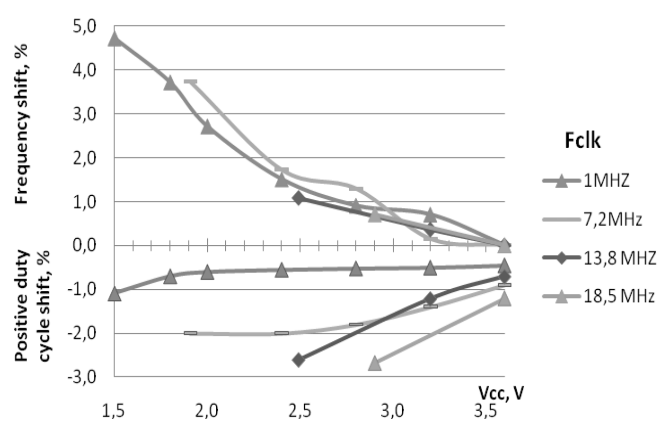

Figure 5. Shift of DCO clock frequency and positive duty cycle comparing to 3.6 V power supply

Although, the dependences, presented on Fig. 5 would not significantly influence the work of the system in most cases, but for some applications (for example, the ones which require synchronization), discovered dependences can play an important role.

The main difficulty with the practical implementation of supply voltage control is that for contemporary microcontrollers it cannot be done without using external components, which would increase the price and power consumption of a node as well in active and in low power modes. The second problem is that the efficiency of voltage conversion circuits for low load currents, which are typical for WSN nodes, is usually not very high. For example, in [8] a system that allows microcontroller to control its supply voltage was presented. This system is based on TPS63000 voltage converter and MCP4110 potentiometer. From [15] it can be seen that TPS63000 has the quiescent current around 50 µA. At the same time, the low-power sleep mode current consumption for eZ430-RF2500 node (both microcontroller and radio chip) is around 1 µA. So, for this case, the addition of voltage control schematic would increase the sleep mode power consumption for around 50 times, which is hardly acceptable, especially with such limited resources, which energy harvesting systems have. Although it can be possible to make the system, which would switch the voltage control system off, when the microcontroller is in sleep mode and would turn it on as soon as microcontroller would switch back to the active mode, but that would increase the complicity and price of the node even more. However, such solution would enable adjusting the power consumption of the voltage convertor during the low power mode as low as 1 µA. On the other hand, one should take into account that according to [15], the efficiency of voltage conversion for typical for WSN microcontroller operation output currents (up to dozens mA) is only around 70%.

So, it can be concluded that voltage control is a quite effective way to lower the power consumption of the node if the node requires to make regular long and heavy calculations, like e.g. in biomedical systems, for which such system was proposed in [8]. In the case, if the node does not need to make heavy calculations or uses long low-power sleep modes, the efficiency of voltage regulation usage should be carefully estimated and compared to the current consumption of the voltage conversion system itself and its influence on power consumption in sleep modes.

C. *Microcontroller program emplacement*

Another option that can influence the power consumption of the node is the location of program code. This option is relatively rarely used and has not been studied yet jointly with other working mode parameters to the best of our knowledge. In [16] we have already marked that running the program from microcontroller RAM memory allows to lower the power consumption comparing with running the same program code from microcontroller internal Flash memory. During this work, we have also evaluated the work of the same test program, which we used for subsections II.A and II.B running from microcontroller RAM memory. The resulting 3D plot for power consumption is presented on Fig. 6.

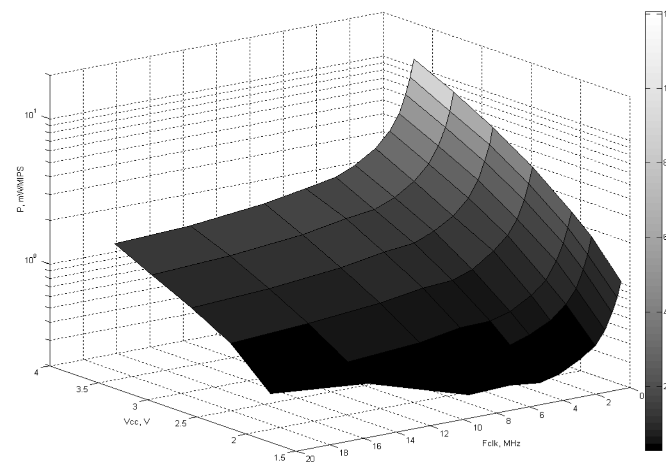

Figure 6. Dependence of microcontroller supply voltage and clock frequency on node power consumption during calculation (RAM program)

Comparing Fig. 6 and Fig. 3 it is possible to see, that usage of RAM for storing the program code allowed not only to lower the power consumption, but also allowed to lower the supply voltage thresholds significantly. It can also be concluded that the optimal clock frequency from the point of power consumption had increased comparing with running the program from Flash and is now around 8-12 MHz. The reason for that is that usage of lower supply voltages for higher frequencies allowed to lower the current, consumed for these modes.

To emphasize the difference of power consumption for different program emplacement cases, Fig. 7 presents the chart of the power efficiency profit for the program running from RAM relatively to running from Flash memory.

Fig. 7 shows that the average profit for power consumption for the cases, when the program can be run by both memory banks is around 5-10% and it slowly increases when the supply voltage increases. Nevertheless, for low supply voltage values in the cases when running the program from Flash was not possible (in that case, for comparison was taken the lowest power consumption value for running using same clock frequency) – the profit becomes very significant and for 18.2 MHz clock frequency reaches 2.5 times.

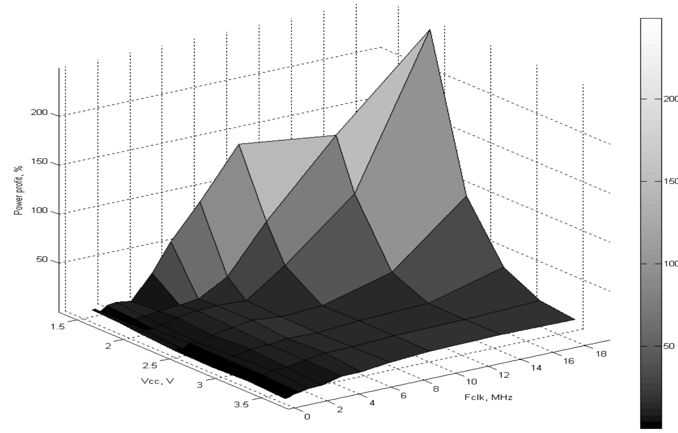

Figure 7. Profit of power consumption for the same program running in RAM comparing with running in Flash memory

Although, as it was shown, the program emplacement can lower the power consumption of the node significantly, but there are some limiting factors for using this approach. The main of them are:

- The limited size of RAM – usually it is much smaller than Flash and should be able to handle both program code and program data.
- Unavailability of interrupts – the interrupts of contemporary microcontrollers are situated at vectors in Flash memory, processing of which requires to have higher supply voltage. If an interrupt would happen when the microcontroller is running low supply voltage – the microcontroller would reboot.
- Energy awareness of RAM – RAM is able to store the data only till the power supply is available – on power down, the data soon would be lost.

So, it can be seen, that program emplacement influences the node power consumption and, in some cases (for example, when the node does not require to control its environment during data processing and the interrupts can be switched off) or for the case of extremely simple programs, the usage of RAM for running the program can be used to increase the power efficiency.

III. INFLUENCE OF MICROCONTROLLER POWER CONSUMPTION ON SYSTEM LIFETIME

In previous parts, we have evaluated the influence of different WSN microcontroller working mode parameters on the system current consumption. Quite often nowadays the lifetime of a system working from the battery is estimated using the nominal capacity of the battery, which is measured for some specified output currents. Unfortunately, for other output currents, as it was shown in [8], the battery capacity could differ significantly from the nominal one. An addition of an energy scavenging feature makes all even more complicated – as such systems are able to get the energy from its environment during runtime, but very often it is impossible to predict when energy harvesting would become available or unavailable. Later in this part we are going to evaluate the influence of parameters, described in previous section, on the node lifetime for two cases: when the node would be supplied using a normal battery and if for node supplying would be used the light energy harvesting system. The node lifetime would be estimated using the number of instructions, which the node can handle using available battery charge.

A. *Lifetime of the node running from a battery*

For estimating the WSN node lifetime if it runs from the battery we used the model presented in [8] for CR2450 battery. Based on that data and our current consumption measurement presented in the previous section we estimated the amount of operations, which a node can make using the battery charge for the cases when the program was in RAM and Flash. The resulting curves are presented on Fig. 8 for the case without the supply voltage control.

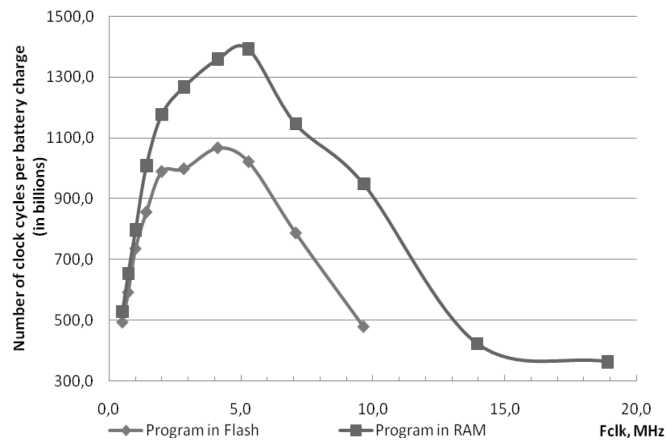

Figure 8. The number of clock cycles per CR2450 battery charge for different microcontroller clock frequencies and program placements

From Fig. 8 it is possible to see that the clock frequency, which maximizes the number of operations is around 5 MHz, which is lower, than the optimal frequency (the estimations were made for average battery voltage, which is equal to 2.6 V), found in previous part and which minimized the amount of energy required per operation. The reason for that is the difference of energy available for different current consumption values for CR2450 battery (the figure can be found in [8]).

The other result, which can be seen from Fig. 8, is that usage of RAM memory for program running allows to improve the lifetime of the node for optimal settings for more than 40% comparing with running the same program from Flash.

B. *Lifetime of the node using energy harvesting from light*

For evaluating the lifetime of the system with the usage of energy harvesting, we used TI eZ430-2500SEH development kit, which used 2.25 inch x 2.25 inch solar panel, energy control chip and thin-film rechargeable EnerChips for energy storing. Although the capacity of EnerChips is quite small – only 100μAh [17], it allows to use low energy, collected from the environment for recharging and to realize numerous recharging cycles. The energy harvesting system also has its own controlling system, which automatically disconnects the load, when EnerChips are almost discharged, and similarly system automatically connects the load as soon as EnerChips will be charged up to some level. Therefore, we have made the measurements for available energy in two opposite cases – when EnerChips were fully charged and just after the energy harvesting system had made the automatic connection after previous discharge. For both cases, the system during tests was in the normal indoor light of around 275 Lux.

Fig. 9 presents the curve for available energy for different current consumption and Fig. 10 presents the amount of operations, which the node can conduct for EnerChips charge.

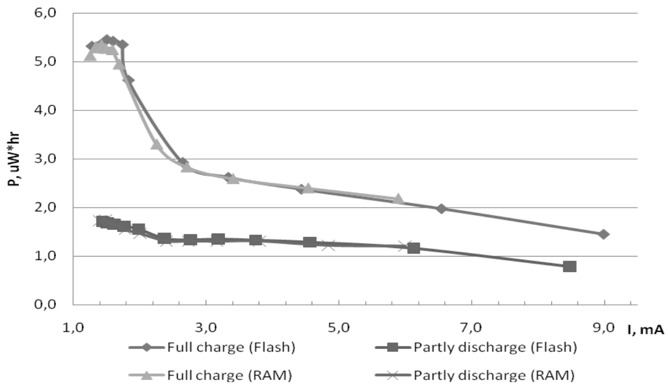

Figure 9. Available energy from EnerChips depending on system consumed current

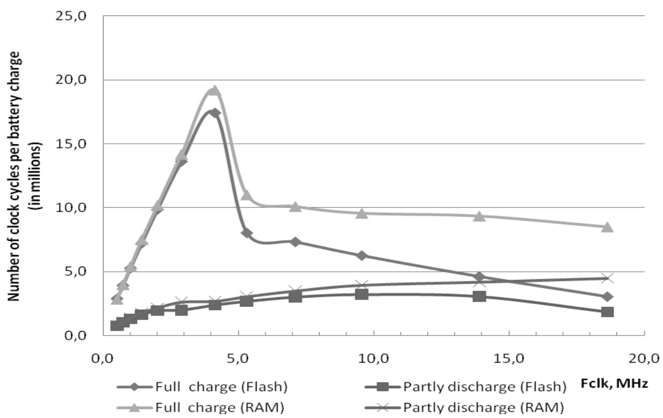

Figure 10. The number of clock cycles per energy harvesting EnerChips charge

Fig. 10 reveals that for the fully charged system with energy harvesting the optimal from the point of the maximum number of operations would be the frequencies of around 4 MHz, which is lower than the frequency, which maximize the lifetime for the same system working from the battery. Also it can be concluded that the optimal mode settings are different for different charge levels – for the partly charged system, the most energy efficient appeared to be high clock frequencies. Again, as it was and for battery supplied and simple power consumption measurements, the usage of RAM for storing the program for high clock frequency appeared to be much more effective, than the usage of Flash memory.

IV. Discussion and Conclusions

Microcontroller is one of the most important parts of every WSN node. In this work, we have studied the influence of different microcontroller parameters on WSN node power consumption computational abilities and on the node lifetime. From presented results it is possible to see that changing the microcontroller supply voltage it is possible to lower the node power consumption significantly. Also, it was shown that for each voltage the microcontroller has an optimal clock frequency, which maximizes the amount of instructions performed per consumed energy unit. One novel result that was achieved is that except the supply voltage and clock frequency of the microcontroller, also the emplacement of the microcontroller program influences the power consumption of the node. Our experiments show that placing the microcontroller program in RAM allows to use higher maximum clock frequencies with the same supply voltage as with the program running in Flash memory. This fact can be effectively used to reduce the node power consumption, especially for high microcontroller clock frequencies, by coping often used parts of the program or even the whole program to microcontroller RAM at the beginning of system work.

In the article, we have also evaluated the influence of WSN node consumed current on the node lifetime and the influence of the microcontroller working mode on the node lifetime. That study was made for two different approaches: for a CR2450 battery power supply and for ez430-RF2500-SEH light-energy harvesting and storing system. The experiments showed that the optimal frequency from the point of maximization operations per battery charge for both cases is lower, than the one, which minimizes energy consumed by the microcontroller per operation. The reason for it is in the discharge curves of the power source – the amount of energy, which can be received from the battery, lowers significantly with the increasing of current which is required to increase of microcontroller clock frequency. It was found that the most efficient clock frequency which maximizes the number of operations and therefore the lifetime of the node is different for various power supply sources, and for the energy harvesting system it is even different for various charge and discharge schedule. It can be concluded, that optimization of power consumption for a WSN node (or any other microcontroller based system, which has limited amount of energy) requires not only careful study and planning of peripheral components power consumption, but also requires the study of the power source characteristics.

As the continuation of this research, we are planning to study the influence on hardware parameters for the second requisite part of WSN - the radio chip on the node power consumption and system lifetime. Also we are planning to make the studies and experimental testing for the most used power supply sources influence on the probable WSN node lifetime.

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