Creation of Connections between Sensor Networks and Battery Energy

Mirko Kosanovic[1], Mile Stojcev[2]
[1]Mirko R. Kosanovi is with the High Technical School
A.Medvedeva 20, 18000 Nis, Serbia
mirko.kosanovic@open.telekom.rs

[2]Mile K. Stojcev is with the Faculty of Electronic Engineering
A.Medvedeva 14, 18 000 Nis, Serbia
stojcev@elfak.ni.ac.rs

ABSTRACT: *We studied the active time-slot which helps in the formation of a method. We have developed with the intention to overcome the issue of reliable connection between sensor nodes where the sensor nodes operate with harsh environment condition. We planned to focus how the extension has impact over the reliable connection between Sensor Networks and its battery energy. During implementing we found a substantial change in the battery capacity.*

Keywords: Reliable Connection, Active Time-Slot Extension, Duty Cycling, Energy Efficiency, Lost Packets

Received: 21 March 2022, Revised 8 June 2022, Accepted 30 June 2022

DOI: 10.6025/jnt/2022/13/3/69-75

1. Introduction

Wireless Sensor Networks (WSNs) represent a set of tiny, inexpensive sensor nodes (SNs), installed in almost all areas. They are capable of sensing, processing and communicating among each other independently, thus forming a network structure completely autonomous. Their capabilities are demonstrated in a wide range of different applications including environmental monitoring, transportation, security, and healthcare [1]. The SNs have limited battery power, so prolonging battery life is crucial goal in the design of WSNs due to difficulty and high cost associated with replacing or recharging exhausted batteries. In general, there are two solutions of this problem. The first relates to finding effective methods for optimal use of available energy, while the second one deals with the usage of natural resources as additional sources of energy, i.e. implementation of energy harvesting techniques [2].

In this paper we focus on implementation of a technique called duty cycling as one of the basic approach for efficient usage of available energy. The point of this technique is that a SN most of the time aggressively switches off its electronics part and does essentially becomes disconnected from the network. In this dynamic environment, it is a major challenge to provide correct connectivity to the time-synchronized WSN, besides minimizing the energy consumption. As a consequence of a SN`s local oscillator frequency instability, which causes an error in time synchronization, we introduce the an extension of active time-slot. In this way we generate enough wide time-slot (window) within which we expected to receive the packet, even in a case when several consecutive packets are lost. The cost which we pay for involving this extension is really a minor increase of battery capacity (<0.01 % per year).

2. SN`S Requirements for Timestamp Generation

The SN architecture consists of several building blocks: power supply, sensing, computing, communication, and optional: mobile unit, coordinate unit, time system synchronizer, etc. Time record, within SN architecture, is provided in computing block by clock oscillators and timers. Two different clock oscillators, referred as system clock oscillator (SCO) and local time oscillator (LTO), typically drive the SN. The LTO operates without interruption. In order to provide time signal for maintaining correct timekeeping (local timestamp), the LTO can be configured at scalable rate (generates different time units). For example, the popular Berkeley Mica mote has 4 MHz SCO and external watch crystal oscillator of 32,768 Hz as LTO [3]. The reason for using two separate clock generators within SN is the following: The LTO operates continually in time, contrary to SCO, which decreases or stops CPU activities when enters in different power saving modes. During power saving mode the CPU loses all timing information. Therefore, the SCO for time keeping by itself cannot be used [4]. In our proposal, the LTO is used for determining duty cycle periods and creation of local timestamp, only. When the CPU enters into active mode all time delays are measured with resolution defined by the local SCO. In this way, we improve time resolution measurement and indirectly decrease the time synchronization error.

Most hardware oscillators have not so stable and precise frequency. This means that they never generate accurate time intervals by which timestamps are created. Crystal oscillator ticks are of slightly different rate due to impact of manufacture techniques, ambient temperature, pressure, battery voltage, oscillator aging, and other effects. Let the crystal oscillator accuracy be in the range from 1 ppm (parts per million) up to 50 ppm. This implies that if the nominal frequency of a crystal oscillator is only 1MHz, the time between two SNs may drift (1-50) µs per second. Even a very small frequency deviation would bring a time uncertainty of about 0,864 – 4.32 seconds per day [5]. Because of this, timestamps in SNs are different. Many applications in WSN require tight time coupling. This means that timestamps have to be identical in all SNs. In order to realize this, time synchronization protocol has to be implemented.

Synchronized network time is an essential aspect for energy efficient scheduling and power management of SNs. It allows SNs to shutdown their RF transceivers and other peripherals, even microcontrollers, to enter into power saving mode, and later to return to normal operating mode. But, accurate clock synchronization of SNs within a heterogeneous network is not a trivial task. Although all SNs run with the same operating frequency, they all have a margin of errors. This means that they do not run at exactly the same speed. This deviation is termed frequency error, and is defined as frequency drift. Due to the frequency drift, SN may wake-up too soon or too early to receive packet. To avoid this shortage we propose that each SN piggybacks its own local timestamp during transmitting its packet. The receiving SN creates local table in which each entry saves a clock difference between the receiving and sending SN. In this way, we provide tight time synchronization between neighboring SNs [5].

3. Duty Cycling Definition

Different techniques for reducing power consumption are used, with aim to minimize the energy consumption in SN [2, 3]. Duty cycling is effective and commonly used technique to lower the rate of energy consumption. The idea behind this is clear. Keep hardware in a low power sleep state except on infrequent instances when the hardware is needed. However, duty cycling leads to more complex communication patterns that include polling, and scheduling the channel. As the radio operation dominates in the SN power budget [6], the main way to limit the power consumption is to limit the time for which the radio circuitry is switched on. This implies intermittently switching the radio on and off. The periods during which a SN's radio is on or off are known as active (T_{ON}) and inactive (sleep) period (T_{OFF}), respectively. The complete working period, T_{Σ}, (see Figure 1) is equal to:

$$T_{\Sigma} = T_{OFF} + T_{ON} \tag{1}$$

The fraction of the time that a SN's radio is on, in respect to the complete time synchronization period, is referred as duty cycle (DC), and is defined as:

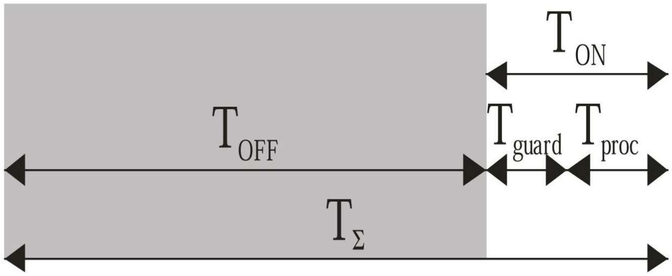

Figure 1. The complete SN‘s working period

$$DC = \frac{T_{ON}}{T_{\Sigma}} = \frac{T_{guard} + T_{proc}}{T_{OFF} + T_{guard} + T_{proc}} \tag{2}$$

where $\boldsymbol{T_{proc}}$ corresponds to the processing time needed for sensing, data processing, data storing, and transmitting packets; $\boldsymbol{T_{guard}}$ represents a guard time. During operation, the frequency skew results in relative clock drift between nodes. As a result, nodes must include a guard time. The guard time is equal to the maximum drift, and linearly depends on T_{Σ}. If s_x ($\Delta f/f$) is the frequency skew, and T_{Σ} is the total working period, then the minimum guard time becomes $T_{guard}=2T_{\Sigma}s_x$. It is obvious that the SNs whose active periods do not overlap cannot communicate with each other.

4. Packet Delivery

The strength of electromagnetic signals decreases rapidly as the distance between the transmitter and receiver increases. In addition, a receiver may receive signals not only from the intended transmitter but also from other transmitters if they are using the same carrier frequency, i.e. interference appears. The receiver may receive multiple signals from the same transmitter because electromagnetic waves can be reflected back from obstacles such as walls, ground, or objects. All this makes the signal less recognizable. On the other side, it is well known that in industrial environments we have very high level of electromagnetic disturbances. As a consequence of all aforementioned, we have very high percent of lost packets, i.e. the packet rejection ratio is in average in the range from 40 % to 70 % [7, 8]. Having this in mind, some modifications of T_{ON} period during receiving process are necessary to involve, to compensating lost packets. In principle, there are two solutions for this problem. In the first one, when the SN does not receive a synchronization packet in time, it updates its local time according to a value obtained during the last correctly received packet. This solution is simple but has one serious drawback. Namely, when several consecutive packets are not correctly received, T_{ON} period can slide out of borders, within which it is expected to appear. The second solution is similar to the first except that in addition it extends its guard time, T_{guard}. In this case, when the SN does not receive packet in time, it updates its local time according to the value obtained during the last correctly received packets, and in addition, in the next synchronization cycle the guard period Tguard is prolonged for additional period, T_{ext}. In our case, we assume that during T_{proc}, the period T_{ext} appears because of SCO instability, and time delay needed for creating the timestamp during T_{proc}. For T_{proc}=10,004 ms, SCO frequency of 1 MHz, and frequency instability of 50 ppm, we obtain T_{ext} = 0.5002 μs. By involving time correction for T_{ext}, a possibility to miss the T_{ON} period, due to instability of SCO, in a case when several consecutive packets are not correctly received, is drastically reduced.

During our analysis, we assume that the probability density function (PDF) of all missed packets corresponds to Binomial one, while for consecutively missed packets to Normal Gaussian distribution. According to the aforementioned, Eq. (2) can be written as:

$$T_{\Sigma} = T_{OFF} + T_{proc} + T_{guard} + T_{ext} \quad = T_{OFF} + T_{proc} + 2 * T_{\Sigma} * s_x + \frac{\sum_{i=1}^{n} i\upsilon_i k T_{ext_i}}{m} \tag{3}$$

where the limit value n depends on the value of a standard deviation, σ. Without loss of generality, we take that nmax = 26, because the probabilities for all σ values are almost equal to zero for $n > 26$ (see Fig. 2). Equation (2) defines the relationship among active, sleep and guard periods. Here T_{ext} corresponds to the average error during receiving all packets; i is the number of consecutively missed packets; v_i is the probability of consecutively missed packets; k is a total number of lost packets; and m corresponds to the total number of delivered packets.

5. Proposed Solution Evaluation

5.1. Average Current

Our solution uses duty cycling. The CPU of SN is based on low power microcontroller MSP430F123 and its communication part on the RF modulator CC 2420. The MSP430 runs in two operating modes, Active with 300 µA at 1 MHz and 3 V power supply, and Low Power Mode 3 with power consumption of 0,7 µA. MSP430 uses two quartz oscillators, LTO (32 kHz) and SCO (1 MHz). LTO is always active, while SCO is active during T_{proc} and T_{guard} periods. In transmitting mode the RF modulator consumes 17.4 mA, in receiving mode 19.7 mA, and in sleep mode 1 µA. Data transfer rate is 128 kbps and packet length is 64 byte. The initial duty cycle value, which is used as parameter for evaluating the power consumption, can be within a range from 1 % down to 0.01 %. The accuracy of a time crystal oscillator, S_x, is 50 ppm. The capacity of a Lithium-ion battery is 560 mAh. A sensor MS55ER for barometricpressure, with average current consumption of 1 mA, is connected to the SN.

The average current consumption, I_{AVR}, during the period T_Σ is equal to:

$$I_{AVR} = \frac{(T_{PROC} + T_{guard}) * (I_{ACPU} + I_{ARF} + I_{sen}) + T_{OFF} * (I_{SCPU} + I_{SRF})}{T_\Sigma} = \frac{T_{ON} * (I_{ACPU} + I_{ARF} + I_{sen}) + T_{OFF} * (I_{SCPU} + I_{SRF})}{T_\Sigma} \tag{4}$$

where $T_{ON} = T_{proc} + T_{guard}$; and I_{ACPU}, I_{ARF}, Isen and I_{SCPU}, I_{SRF} correspond to current consumption of the CPU, transceiver, and sensor, respectively, during time period T_{ON} (active) and time period T_{OFF} (sleep), respectively. Substituting Eq. (2) into Eq. (4), we obtain:

$$I_{AVR} = DC * (I_{ACPU} + I_{ARF} + I_{sen}) + (1 - DC) * (I_{SCPU} + I_{SRF}) \tag{5}$$

5.2. Distribution of Consecutively Lost Packets

Packet delivery is a result of the signal to noise ratio (SNR). The SNR describes how strong the intended RF signal is in comparison to additive Gaussian noise. SNs with build-in RF modulator CC2420 usually use the receive signal strength indicator (RSSI) as the estimator of the link quality. In general, links with an average RSSI above -87 dBm are good links. Below this threshold, there is no clear correlation to RSSI. Detailed empirical analysis, which relates to distribution of packets delivery, can be found in [7].

In WSN environment, the influence of externally induced magnetic fields, interference, multipath reflections, noise, and other disrupting traffic factors, is commonly present. Due to this, a large number of packets are received with errors. Packets with errors are rejected by the receiver. Each lost packet has impact on error appearance in time synchronization. This error increases as the number of consecutively lost packets increases.

The amount of a DC factor has direct impact on SN`s power consumption. T_{guard} as constituent of T_{on} (see Figure 1), is component of variable time duration and in our proposal, according to Eq. (3), directly depends on the number of consecutively lost packets. In order to determine the probability of consecutively lost packets we use Normal Gaussian distribution. The results which relate to the number of consecutively lost packets for different values of σ (standard deviation) are presented in Figure 2. The standard deviation, σ, corresponds to the number of packets that deviate from the average value of the total number of lost packets. As the distance between a sender and receiver increases, the strength of a received signal decreases (the signal to noise ratio decreases and link operates close to noise floor) the number of lost packets increases, too. A combination of all aforementioned effects, results in different PDF values, whose effects are sketched in Figure 2. In general, curves denoted with lower σ values (see Figure 2), are typical for shorter distance between the sender and receiver. This means that for shorter distances the dispersion of consecutively lost packets is smaller (i.e. narrower).

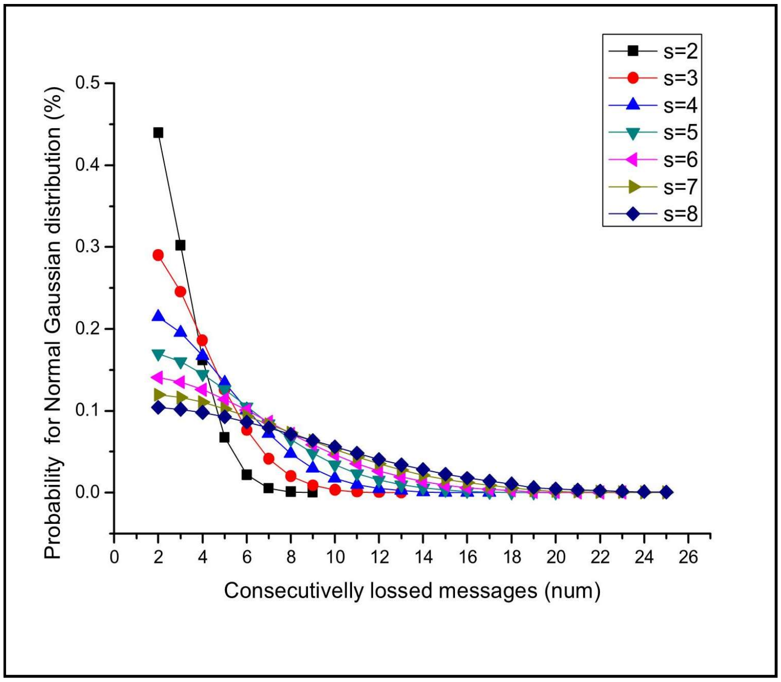

Figure 2. Probability of consecutively lost packets for Normal Gaussian distribution for different σ

5.3. Power Consumption and Battery Capacity

Taking into account the results presented in Figure 2 according to Eqs.(2), and (5), we can determine now in which way the number of lost packets have impact on SN`s power consumption. Our analyze includes SN`s power consumption with SCO of 1 MHz., for a period of one year, with different T_{Σ}(1s, 1 min, 1 h), and for standard deviation σ = 2. The calculated results which relate to the average current I_{AVR}, *DC* factor, and battery capacity (*BC*), are given in Table 3. Let note that our analysis takes into account the consumption of SN needed to carry out the communication among SNs, only. It did not include other activities of the SN such as: A/D and D/A conversions, data processing, data storing, packet transfer, packets aggregation, routing, and so on.

For one-year working period, the increase of *BC* with respect to its full capacity, when the duty cycle extension is implemented, is given in Table 3. In a concrete case dutycycle extension is achieved by prolonging the time duration of a guard period, T_{guard}. For IPI equal to one second, and for PRJR in the range from 40 % to 70 % the increment of BC is always less than 0.01 %. These results imply that due to duty cycle extension higher reliability in time synchronization (for a case when large number of packets is lost) is achieved, at the cost of very low (< 0,01 %) increase of battery capacity.

Diagrams that show the needed BC (for one year working SN period) in term of different standard deviation starting from σ = 2 up to σ = 8 (for PRJR from 40% to 70%, as parameter), for IPI T_{Σ}=1 h, are given in Figure 3.

6. Conclusion

In battery-powered SN, as constituents of WSN, multi-year operation on a single coin-cell battery is a crucial issue. Several methods to cope with efficient energy consumption have been proposed in literature. In this paper we present one simple an efficient technique named extension of active timeslot. Principle of operation of the proposed scheme is based on usage of duty cycling technique. It allows us to achieve correct time synchronization in SN operation, even in a case when large number of consecutive packets is lost, and relatively high instability of the local SN oscillator exists. The proposed solution and its implementation are simple. It does not require great resources. The obtained results show that, for single year working period, when the packet rejection ratio varies from 40 % to 70 %, and inter-packet interval is one second (worst case) an increase of battery capacity less than 0.01 % is needed.

	I_{AVR} [μA]	DC [%]	BC [mAh]	Increasment of BC [%]
$PRJP_1$=70 %				
T_Σ=3600	3.858317	0.010279	33.79885355	0.00016
T_Σ=60 s	7.304285	0.026689	63.98554074	0.00498
T_Σ=1 s	214.3505	1.012703	1877.710412	0.01013
$PRJP_2$=60 %				
T_Σ=3600	3.858316	0.010279	33.79884622	0.00014
T_Σ=60 s	7.304234	0.026689	63.98508973	0.00428
T_Σ=1 s	214.3474	1.012689	1877.68327	0.00869
$PRJP_3$=50 %				
T_Σ=3600	3.858315	0.010279	33.79883876	0.00012
T_Σ=60 s	7.304182	0.026689	63.98463767	0.00357
T_Σ=1 s	214.3443	1.012674	1877.65612	0.00724
$PRJP_4$=40 %				
T_Σ=3600	3.858314	0.010279	33.79883117	0.00010
T_Σ=60 s	7.304131	0.026688	63.98418463	0.00286
T_Σ=1 s	214.3412	1.012659	1877.628962	0.00579
$PRJP_0$=0 %				
T_Σ=3600	3.85831	0.010279	33.79879793	1
T_Σ=60 s	7.303921	0.026688	63.9823507	1
T_Σ=1 s	214.3288	1.0126	1877.520164	1

Table 1. Needed Battery Capacity for One Year Period

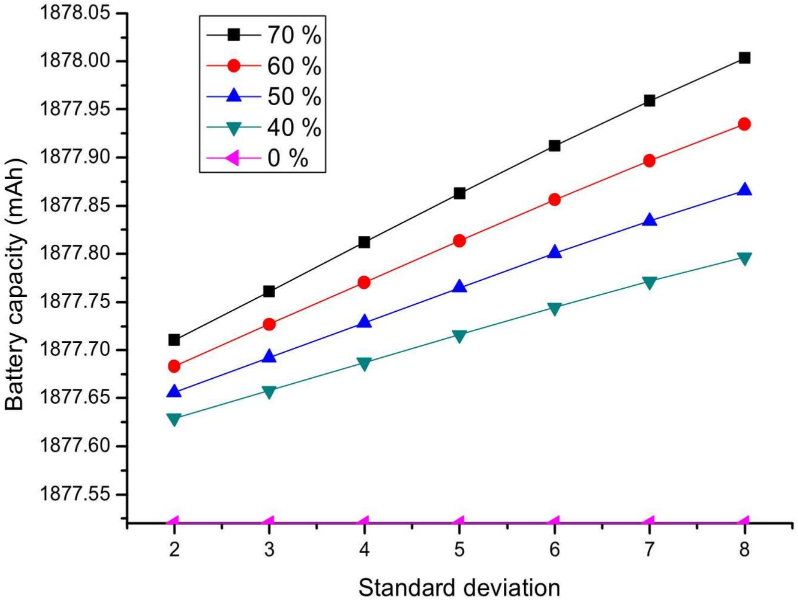

Figure 3. Battery capacity for different PRJR for single year SN`s working period

Acknowledgement

This work was supported by Serbian Ministry of Science and Technological Development, project No. T-32009 - "Low Power Reconfigurable Fault Tolerant Platforms".

References

[1] Akyildiz, I.F. & Vuran, M.C. (2010). *Wireless Sensor Networks*. John Wiley & Sons: Chichester.

[2] Stojcev, M., Kosanovic, M. & Golubovic, Lj. Power management and energy harvesting techniques for WSN, 9 International Conference on Telecommunications in Modern Satellite, *Cable and Broadcasting Services IEEE*, Nish, 2009.

[3] Ping, S. (15/12/2012) Delay measurement time synchronization for WSN. www.intelresearch.net/Publications/Berkeley/081120031327137.pdf, acc.

[4] Schmid, T., Shea, R., Friedman, J., Charbiwala, Z., Srivastava, M.B. & Cho, Y.H. (20/10/2012) On the interaction of clocks and power in embedded sensor nodes. Available on nesl.ee.ucla.edu/fw/thomas/schmid2009techreport.pdf, acc.

[5] Kosanovic, M. & Stojcev, M. Delay compensation method for time synchronization in wireless sensor networks, 10. International Conference on Telecommunications in Modern Satellite, *Cable and Broadcasting Services*, Nish, 2011.

[6] Raghunathan, V., Ganeriwal, S. & Srivastava, M. (2006) Emerging techniques for long lived wireless sensor networks. *IEEE Communications Magazine*, 44, 108–114 [DOI: 10.1109/MCOM.2006.1632657].

[7] Srinivasan, K., Dutta, P., Tavakoli, A. & Levis, P. (2010) An empirical study of low power wireless. sing.stanford.edu/pubs/sing-08-03.pdf, acc.. *ACM Transactions on Sensor Networks*, 6, 1–49 [DOI: 10.1145/1689239.1689246].

[8] Rosberg, Z., Liu, R.P., Le Dinh, T.L., Dong, Y.F. & Jha, S. (2010) Statistical reliability for energy efficient data transport in wireless sensor networks. www.cse.unsw.edu.au/~ydon/publications/winet.pdf, acc.. Wireless Networks, 16, 1913–1927 [DOI: 10.1007/s11276-009-0235-5].