Modeling Energy Consumption for RF Control Modules

Barış ORHAN
VESTEL Electronics
Manisa, Turkey
baris.orhan@vestel.com.tr

Engin KARATEPE
Dept. of EEE, Faculty of Engineering
Ege University Izmir, Turkey
engin.karatepe@ege.edu.tr

Radosveta SOKULLU
Dept. of EEE, Faculty of Engineering
Ege University Izmir, Turkey
radosveta.sokullu@ege.edu.tr

***Abstract* — Due to the restricted energy capacity of wireless nodes, development of strategies and protocols to reduce power consumption is a current research topic. Providing a simulation model of the power consumption of a wireless node taking into consideration the specifics of its hardware platform profile and the algorithm, which is running on it before the design stage will help designers predict the possible problems and adaptivity of the software and hardware with less time and effort. In light of this, the article presents a Semi-Markov Chain based model and the related lifetime analysis of a wireless module operating in an event-triggered application scenario. The wireless node's operation pattern is modeled mathematically and equations are derived to provide its lifetime prediction using MATLAB. The lifetime is examined as a function of the channel noise and the arrival rate with defined hardware and software parameters. A case study is presented with simulation results and real life measurements, based on SoC (System on Chip) ICs (Integrated Circuits), communicating using RF4CE(Radio Frequency for Consumer Electronics) protocol.**

Keywords - Energy consumptio, Node Lifetime, RF4CE, Semi Markov Chains

I. INTRODUCTION

In the last couple of years, a combination of consumer demand for more efficient integrated home networking systems and a steep drop in the price of hardware fueled by manufacturing process improvements has resulted in a noticeable upward cycle of research in the field of RF (Radio Frequency) devices for consumer electronics. Because of the increased range of applications and the inherent physical restrictions, wireless networks and RF communications continue to attract the attention of the research community. Major design factors like limited power capacity and long lifetime necessity combined with the variability of the wireless communication media push further the search for new hardware platforms to meet these requirements. This continuous cycle of adapting new platforms to new wireless applications requires minimization of the design and evaluation time, which in turn creates the demand for suitable models and tools to assure that.

In this paper a numerical and simulation model for the estimating the lifetime of wireless RF control modules used in consumer electronics is presented. The paper is organized as follows: in the first part a short survey of related work is provided followed by detailed description of the proposed mathematical model. Section IV presents real life measurements taken to validate the proposed model. In Section V, the simulation results are presented followed by discussion on the specific relation between the RF module's hardware platform lifetime, the event arrival rate and the communication channel characteristics. Hardware and software parameters are defined for the MATLAB simulation model based on datasheets of the considered hardware platforms and the RF4CE specifications. [1-3]

II. RELATED WORK

The technological restrictions inherent to the IR (InfraRed) devices used in consumer electronics, together with the fact that the components used in the production of the RF devices have come to a price level suitable for mass production have triggered the design and development of new RF devices for consumer electronics [4]. Among the major advantages the RF technology brings to the market are the increased functionality and the potential for reducing power consumption. This in turn makes the question of wireless modules' power consumption design and analysis an important research issue [5]. However, research on wireless nodes so far has focused mainly on extending the lifetime of the network as a whole, thus research attention has been predominantly given to the MAC(Media Access Control) layer and network layer operation, protocols and optimization [8-10]. Together with this, little has been done related to modeling, studying and comparing the performance of different wireless node platforms from the point of view of long term lifetime evaluation. In some recent sources [6, 7, 11] the question of power consumption of wireless modules at the hardware level and its more detailed functioning has been modeled and investigated with the purpose of defining ways for its possible reduction. Several different suggestions can be found regarding the way power consumption at the hardware level should be modeled. In [6] analysis of the network wide power consumption is carried out based on hybrid automata modeling and the calculation of the consumption of each node. The lifetime of the network is evaluated as a function of the distance from the nodes to the sink. The authors of [7] propose Markov Chains to be used where each possible state of the operation cycle is modeled as part of the chain. For their study the authors define 6 energy states and the transitions between them. In another work, [11], details of PowerTOSSIM, a simulation tool specifically oriented towards modeling power consumption in wireless sensor networks is presented. In calculating power consumption PowerTOSSIM provides possibilities for taking into consideration the details of the hardware characteristics of the nodes. Different from these the authors of [12, 13] present a model for evaluating the network lifetime based only on the hardware characteristics of the nodes and the application scenario. According to them the combination of hardware characteristics and the requirements imposed by the application scenario are the most important factors in determining the lifetime of a wireless node.

Wireless sensor networks design and operation is strongly application oriented. Thus, since most applications can be classified as either monitoring or event tracking, their operation can be related to either scheduled or event triggered scheme. For the RF control module under consideration the wireless node operates in an event triggered mode. In this mode the node spends a comparatively long time in sleep or idle mode in order to preserve energy and wakes up for receiving or transmission only when there is an event detected. After processing the event and transmitting the required information to the sink or to a neighbor node it returns to low power state. On the other hand monitoring applications require that the node awakes at specific predefined intervals to collect and process information. While the aim in event triggered operation is optimizing both the sleep and processing energy consumption, in schedule driven operation most important is optimizing the schedule of each individual node in order to increase the lifetime of the network as a whole.

In this work, we present a Semi-Markov Chain based model of a wireless module, the new generation RF remote control module, which has recently become very popular in consumer electronics. Furthermore we use this model and the specific hardware characteristics of two well accepted hardware platforms to analyze its long term power consumption, especially stressing on its relation to the event arrival rate and the conditions of the transmission environment. The model is based on wireless SoC (integrated CPU(Central Processing Unit) and radio modules), ,which are among the latest achievements in consumer electronics hardware and the only accepted so far in this field network communication standard, RF4CE [1].

III. MODEL OVERVIEW

In this section, the proposed Semi-Markov Chain model of the wireless node is discussed. A wireless sensor node's main functions are to sense an event and transmit information about it. For event based applications, like the one discussed in this paper, each event will trigger a sequence of operations to be carried out, which form an application specific execution cycle. Furthermore, the cycle can be decomposed into a series of computational and communication tasks. Each of the tasks in its turn can be further broken down into states related to the operation of the CPU, the radio and the specific communication standard used like receiving, listening to the channel, transmitting and processing. Each state can be uniquely associated with a specific power mode. These states (power modes) are defined in Table 1. The long term power consumption of the node will depend on the specific state, its duration and the number of times it is executed. So our aim is to model these states from their power consumption point of view taking into account their duration and frequency of occurrence. For this purpose the following assumptions have been made: a) the arrival of the events is assumed to be Poisson distributed b) the duration of time a node spends in each of the states is random.

TABLE 1 POWER STATES OF THE RF MODULE

Power Mode	**CPU**	**Radio**
S1	OFF	OFF
S2	ON	OFF
S3	IDLE	TX
S4	IDLE	TX
S5	IDLE	TX
S6	IDLE	OFF
S7	IDLE	RX
S8	IDLE	RX
S9	IDLE	RX

In the long run, the randomly distributed times a node will be found in each of the above states and the duration spent in each state for a certain time interval will reach a steady state. Based on the assumptions made in [12], such a process can be described as a Semi-Markov process with Poisson event arrivals. A Semi-Markov process is a stochastic process that changes states in accordance with a Markov chain but takes a random amount of time between changes.

According to the application discussed, the operation of the wireless node is event-triggered and so it keeps its CPU and radio at the lowest power level to reduce power consumption until it detects an event. Thus a simple Semi-Markov Chain model is given in Fig. 1.

For the transmission procedure, according the RF4CE standard, CSMA(Carrier Sense Multiple Access) is used with ARQ(Automatic Repeat Request) retransmission mechanism. States S1, S2, S3 correspond to sleep, processing and transmission, while S4 and S5 are virtual states, which represent the ARQ mechanism. The maximum number of retransmissions without acknowledgment is 3. If unsuccessful the packet is dropped and the node returns to its initial state.

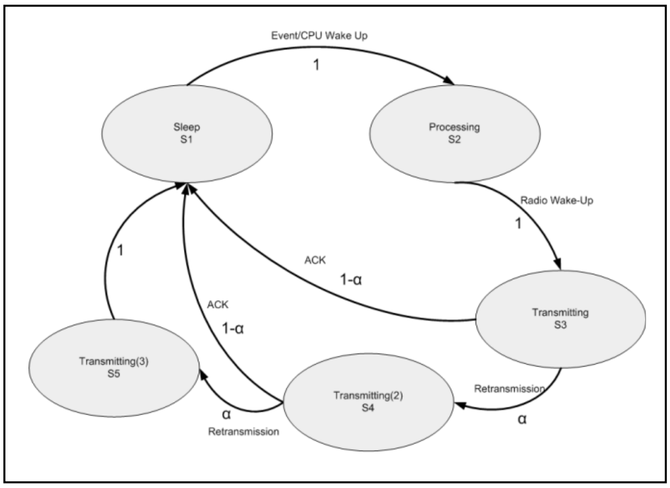

Figure 1.Simple Semi-Markov Chain model of event triggered operation

As defined by the algorithm of the underlying MAC protocol radios should sense the channel before transmission they tend to spend considerable energy listening to the channel. In [14] it is stated that nodes using IEEE 802.15.4 spend less than 50 percent of the energy for actual transmission, while channel listening accounts for more than 40 percent of the energy consumption. During the transmission radios are actually switching between listen and transmit states (S7, S8, S9) because of the requirement to sense the channel before actual transmission of the packet and to listen waiting for acknowledgement after the packet has been transmitted. On the other hand, the CPU makes transitions from processing to idle state while processing (S2-S4). By adding these factors into account, the Semi-Markov diagram is further detailed and updated with embedded chains as shown in Fig. 2.

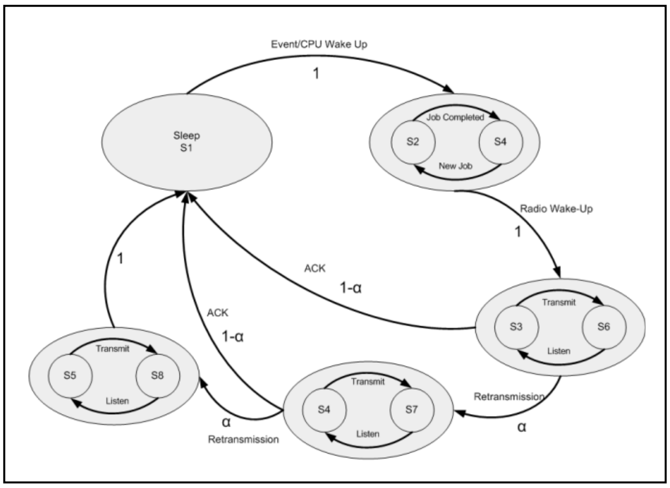

Figure 2.Semi-Markov Chain model with embedded chains

Based on the assumptions and the state definitions for the embedded Semi-Markov Chain made above we now proceed with the analytical model. Let X(t) denote the power state at time t, then {X(t), t≥0} is a Semi-Markov process [15], where the expected value is calculated as;

$$\mu_i = \int_0^\infty x H_i(x) dx \quad (1)$$

and H_i is the random time the semi-Markov process spends in state *i* before making a transition; X_n denotes the nth state visited by the Markov Chain. X_n, n≥0 forms a Markov Chain with transition probability p_{ij}, where $T_{ii}$is the time between successive transitions into state *i* and its expected value is

$$\mu_{ii} = E[T_{ii}] \quad (2)$$

LetT_t, be the total time in *i* during [0,t], then the overall time spent in *i* over the combined time spent in all states (long term amount of time in *i*) is given by:

$$p_i \equiv \lim_{t\to\infty} P[X(t) = i|X(0) = j] = \lim_{t\to\infty} \frac{T_t}{t} \quad (3)$$

If we suppose that the embedded Markov Chain is positive recurrent for n≥0, a stationary probability exists, which is the frequency of visiting each state for a given infinite time duration. Then π_j is the stationary distribution of the embedded Markov chain j≥0. π_j has a unique solution:

$$\pi_j = \sum_i \pi_i \, p_{ij} \, , \sum_j \pi_j = 1 \quad (4)$$

π_j, can be interpreted as the proportion of transitions into state *j* over the sum of all state transitions. Then the following equation holds:

$$p_i = \frac{\mu_i}{\mu_{ii}} = \frac{\pi_i \mu_i}{\sum_j \pi_j \mu_j} \quad (5)$$

The proportion of time spent in *i* to the time spent in all states could be found using (4) and (5). Considering the initial simple model in Fig. 1 and using (2), we can compute:

$$[\pi_1 \ \pi_2 \ \pi_3 \ \pi_4 \ \pi_5] \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 1-\alpha & 0 & 0 & \alpha & 0 \\ 1-\alpha & 0 & 0 & 0 & \alpha \\ 1 & 0 & 0 & 0 & 0 \end{bmatrix} = [\pi_1 \ \pi_2 \ \pi_3 \ \pi_4 \ \pi_5] \quad (6)$$

$$\sum_{1\le j\le 5} \pi_j = 1 \quad (7)$$

(6) and (7) has the unique solution

$$\pi_1 = \pi_2 = \pi_3 = \frac{1}{\alpha^2+\alpha+3}$$

$$\pi_4 = \frac{\alpha}{\alpha^2+\alpha+3} \quad (8)$$

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$$\pi_5 = \frac{\alpha^2}{\alpha^2+\alpha+3}$$

Let p_i be the steady state of Semi-Markov Chain, $\widehat{X}$ average sleep time, $\widehat{Y}$ average processing time and $\widehat{Z}, \widehat{V}, \widehat{W}$ average communication times, then:

$$D_\alpha = \widehat{X} + \widehat{Y} + \widehat{Z} + \alpha\widehat{V} + \alpha^2\widehat{W} \quad (9)$$

$$p_1 = \frac{\widehat{X}}{D_\alpha}, p_2 = \frac{\widehat{Y}}{D_\alpha}, p_3 = \frac{\widehat{Z}}{D_\alpha}, p_4 = \frac{\alpha\widehat{V}}{D_\alpha}, p_5 = \frac{\alpha^2\widehat{W}}{D_\alpha} \quad (10)$$

If T is long enough, the total time elapsed in state *i* is $\lim_{T\to\infty} T_i = Tp_i$. Thus, the total consumed energy in state *i*. is $E_{S_i} = Tp_i \times P_{S_i}$ ($i \in \{1,2,3,4,5\}$) and also transition energy from state *i* to *j* can be calculated by multiplying one transition cost by the average number of transitions from state *i*. to *j*. In state transition calculations, we will only use the wake up costs ($C_p(E_{S_{12}})$ ve $C_r(E_{S_{23}})$) because the sleep cost for both the CPU and the radio is negligible.

Thus, to summarize, the wireless node's long term lifetime estimation can be defined based on three distinct components:

$$A_1 = \{n | X_j = S_1, X_{j+1} = S_2, X_{j+2} = S_3\}$$

$$A_2 = \{n | X_j = S_1, X_{j+1} = S_2, X_{j+2} = S_3, X_{j+3} = S_4\}$$

$$A_3 = \{n | X_j = S_1, X_{j+1} = S_2, X_{j+2} = S_3, X_{j+3} = S_4, X_{j+4} = S_5\}$$

Furthermore, as can be seen from the model in Fig. 1 and Fig. 2, the CPU and the radio have to wake up for entering states S2 and S3. Since $\mu_{ii} = D_\alpha$, average number of cycles during T is $C_T = \frac{T}{D_\alpha}$

C_T : Total transition energy cost during T
k(T): average cycle number during T

By observing the limiting behavior of the function in (11),

$$\widehat{P}_{td} = \lim_{T\to\infty} \frac{1}{T}\left[\sum_{1\le k\le 5} E_{S_k} + C_T\right] \quad (11)$$

the total amount of energy spent at each state, E_{S_i} and the transition energy, C_T over *T*, the average power consumption for an event-triggered node can be calculated as follows:

$$\widehat{P}_{td} = \left[p_1 P_{S_1} + p_2 P_{S_2} + p_3 P_{S_3} + p_4 P_{S_4} + p_5 P_{S_5} + \frac{C_p + C_r}{D_\alpha}\right] \quad (12)$$

$$\widehat{P}_{td} = \left[\frac{\widehat{X}}{D_\alpha} P_{S_1} + \frac{\widehat{Y}}{D_\alpha} P_{S_2} + \frac{\widehat{Z}}{D_\alpha} P_{S_3} + \frac{\alpha\widehat{V}}{D_\alpha} P_{S_4} + \frac{\alpha^2\widehat{W}}{D_\alpha} P_{S_5} + \frac{(C_p + C_r)}{D_\alpha}\right])$$

$$\widehat{P}_{td} = \left[\frac{\widehat{X}P_{S_1} + \widehat{Y}P_{S_2} + \widehat{Z}P_{S_3} + \alpha\widehat{V}P_{S_4} + \alpha^2\widehat{W}P_{S_5} + (C_p + C_r)}{\widehat{X} + \widehat{Y} + \widehat{Z} + \alpha\widehat{V} + \alpha^2\widehat{W}}\right] \quad (14)$$

From the initial model presented in Fig. 1 we can deduct the time dependent state/energy consumption representation given in Fig. 3 for the power profile of an event-triggered wireless node. The average processing and communication time is very small compared to the average sleep time (time when the module is waiting for an event), thus the average sleep time for one cycle is equal to the event inter-arrival time.

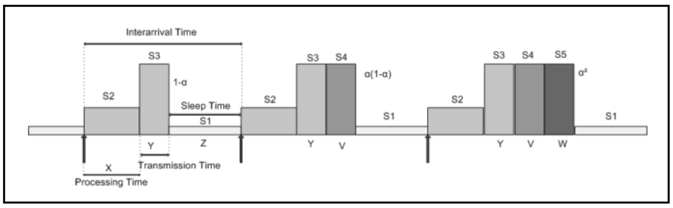

Figure 3.Basic power profile of the event triggered node

If λ denotes the arrival rate and $\widehat{X} = 1/\lambda$ then:

$$\widehat{P}_{td} = \left[\frac{P_{S_1} + \lambda(\widehat{Y}P_{S_2} + \widehat{Z}P_{S_3} + \alpha\widehat{V}P_{S_4} + \alpha^2\widehat{W}P_{S_5} + (C_p + C_r))}{1 + \lambda(\widehat{Y} + \widehat{Z} + \alpha\widehat{V} + \alpha^2\widehat{W})}\right] \quad (13)$$

Thus (13) is the direct analytical expression corresponding to the basic model in Fig. 1. However, taking into account the more detailed model in Fig. 2 we can derive the time dependent representation given in Fig. 4. It has been extended with the inclusion of the embedded states S6, S7, S8 and S9 for the processing and communication tasks.

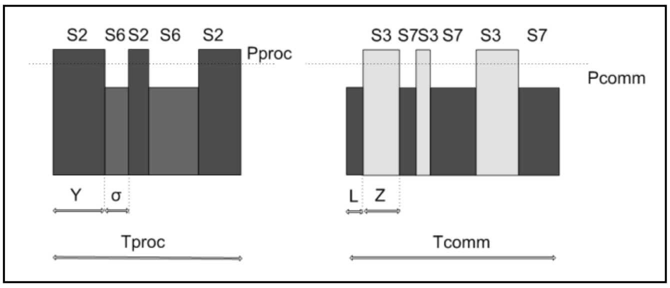

Figure 4.Embedded chains of Markov-chain model

So, the average processing power $\overline{P}_{proc}$ and the average processing time, $\overline{T}_{proc}$, respectively $\overline{P}_{comm}$ and $\overline{T}_{comm}$ are:

$$\overline{P}_{proc} = \frac{\overline{\sigma}P_{S_6} + \widehat{Y}P_{S_2}}{\overline{\sigma} + \widehat{Y}} \quad (15)$$

$$\overline{T}_{proc} = (\overline{\sigma} + \widehat{Y})\,\overline{N}_\sigma \quad (16)$$

$$\overline{P}_{comm} = \frac{\overline{L}P_{S_7} + \widehat{Z}P_{S_3}}{\overline{L} + \widehat{Z}} \quad (17)$$

$$\overline{T}_{comm} = (\overline{L} + \widehat{Z})\,\overline{N}_L \quad (18)$$

where $\overline{\sigma}$ is the average time the CPU spends in idle states, $\overline{L}$ is the average time the radio spends listening, $\overline{N}_\sigma$ is the average number of CPU's idle states, $\overline{N}_L$ is the average number of the radio's idle states. Thus for the average power consumption using (15), (16), (17) and (18) in (14), we get (19):

$$\widehat{P}_{td} = [\frac{P_{S_1}+\lambda((\bar{\sigma}P_{S_6}+\hat{Y}P_{S_2})\bar{N}_{\sigma}+(\bar{L}P_{S_7}+\hat{Z}P_{S_3})\bar{N}_L+\cdots}{1+\lambda((\bar{\sigma}+\hat{Y})\,\bar{N}_{\sigma}+(\bar{L}+\hat{Z})\,\bar{N}_L+\cdots}$$

$$\frac{\alpha(\bar{L}P_{S_8}+\hat{Z}P_{S_4})\bar{N}_L+\alpha^2(\bar{L}P_{S_9}+\hat{Z}P_{S_5})\bar{N}_L+(C_p+C_r))}{\alpha(\bar{L}+\hat{Z})\,\bar{N}_L+\alpha^2(\bar{L}+\hat{Z})\,\bar{N}_L)}] \qquad (19)$$

Dividing the total power by equation derived in (19), the average lifetime for an event-triggered node is calculated as:

$$\widehat{T}_l(\lambda) = \frac{E_{TOTAL}}{\widehat{P}_{td}} \qquad (20)$$

IV. MODEL VALIDATION

In this part, we present some real life measurements in support of the suggested model, taken using wireless node platforms CC2530 and MC13213. The experimental setup includes a serial 10Ω load. The resulting time-voltage graphs in response to an event are given in Fig. 5 and Fig. 6. When turning the radio on, the node performs a sequence of transitions between different states as shown below.

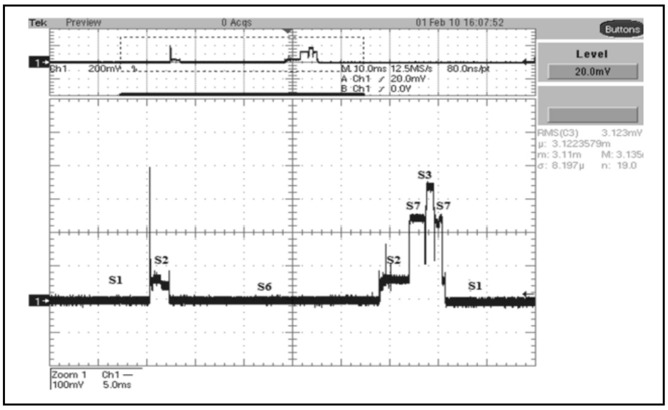

Figure 5.Oscilloscope output for a noise-free channel

Fig. 5 corresponds to the case when the channel is clear and the first time a packet is transmitted a positive acknowledgement is received. Fig. 6 presents the case when

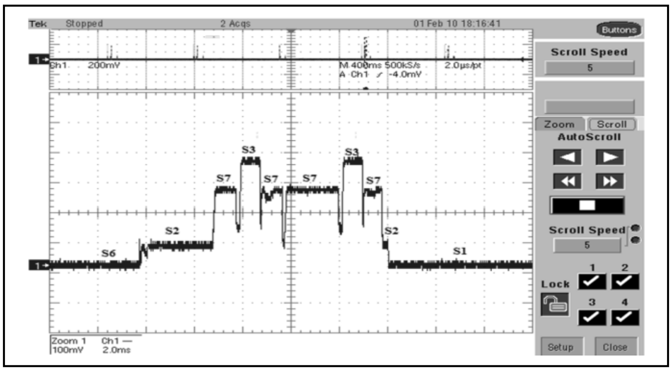

Figure 6.Oscilloscope output for a noisy channel

due to a noisy channel the first transmission was unsuccessful and following retransmissions were required. The states S1 to S7 are as defined earlier in Table 1. The measurements support our selection and definition of the states and the required transitions, given in Fig. 1 and Fig. 2. When the node is not in use it is in state S1, which is the lowest power state, in order to enable long battery life. This state is defined as the deepest possible sleep, using min power. However, coming out of that state is inherently associated with unwanted effects as input jitter. When an event occurs (a key is pressed), the device wakes up on a key press and sets the sleep timer to expire in 25 ms, entering back sleep mode. After this timer expires, the CPU wakes up, reads the pressed key, prepares the packet to be sent, the radio listens to the channel and transmits waiting for acknowledgement. Upon receiving the acknowledgement the CPU and the radio enter back into deep sleep state (S1). In case the first attempt to send the packet is unsuccessful (Fig. 6), the radio and CPU will return to state S7, attempt a second and third retransmission and if again unsuccessful will force return to sleep state. So, when retransmission is required, it is visible that the node does not return to sleep state S1 between the successive trials. It only returns to the initial, low power state (S1) after a successful transmission or if the maximum number of allowed retransmission attempts is reached, which proves the need to define additional states S7, S7 and S9.

V. SIMULATION RESULTS

In this section, the RF control module lifetime is investigated for two different scenarios for the two wireless platforms CC2530 and MC13213. Our main goal is to examine the dependence of the lifetime as a function of the event arrival rate and the channel conditions and then compare the two platforms.

Fig. 7 and Fig. 8 present the results as the number of arrival events per hour increases from 0 to 40 in case of transmission success ratios set to 0.2 and 0.8 respectively. We notice that the lifetime decreases for both platforms as the rate increases and the channel quality is decreased. While the CC2530 platform achieves a determinedly longer lifetime for low arrival rates (5 – 7 events per hour), the decrease in lifetime duration for high event arrival rate (35 events per hour) is higher (nearly 71% compared to 55% for the MC13213 platform). In the long run, the CC2530 platform is more sensitive to channel noise and event arrival rate than the MC13213 platform. Results are given in Table 2.

TABLE 2 PERCENTAGE LIFETIME COMPARISON

Platform	α		λ	
	0.2	**0.8**	**12**	**4**
CC2530	71%	78%	25%	17%
MC13213	60%	64%	20%	11%

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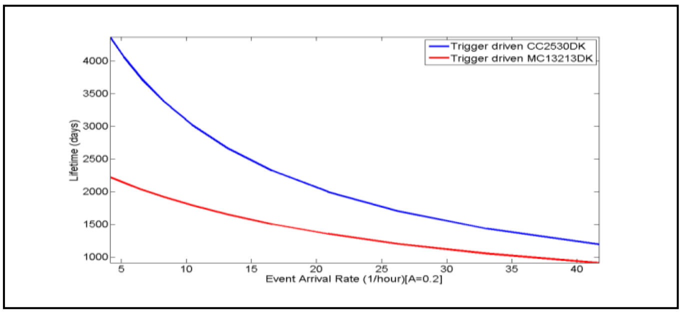

Figure 7.Lifetime prediction for α=0.2

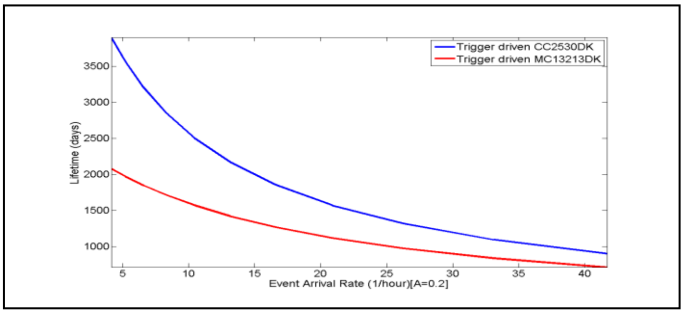

Figure 8.Lifetime prediction for α=0.8

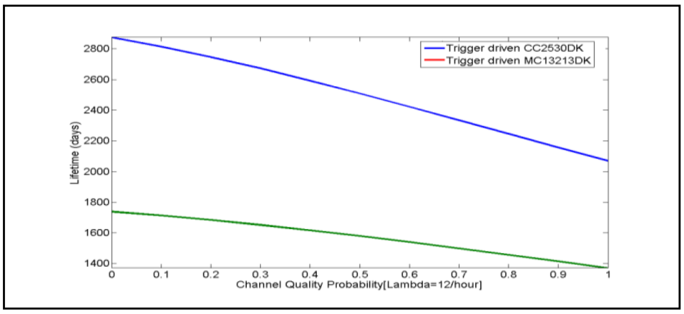

Figure 9.Lifetime prediction for λ=12

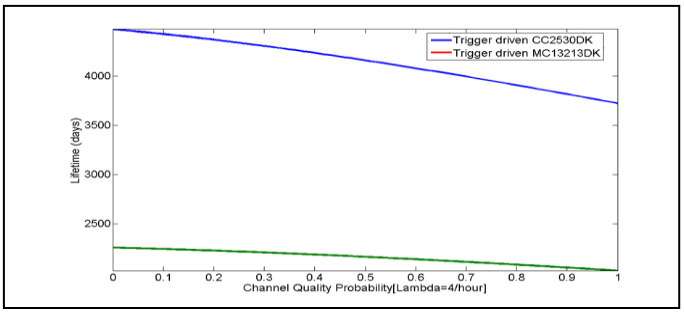

Figure 10.Lifetime prediction for λ=4

Fig. 9 and Fig. 10 give the lifetime prediction for the two platforms as a function of the channel conditions (transmission success ratio) for two fixed event arrival rates 4 and 12 events per hour. MC13213 platform shows less sensitivity to both varying arrival rate and channel conditions. However CC2530 has a longer lifetime for all conditions better performance for all cases. It is worth nothing that the arrival rate is more determinant parameter than channel noise.

VI. Conclusion

In this paper we have suggested a mathematical model, based on embedded Semi-Markov Chains, for the evaluation of the lifetime of an RF wireless module operating in an event-triggered mode. The model is validated using real time measurements for two hardware platforms compatible with the newly approved standard, RF4CE, for RF devices for consumer electronics. Furthermore, simulation results have been presented showing the dependence of the two platforms on the event arrival rate and the channel conditions with the assumption that CSMA with AQR is used.

VII. ACKNOWLEDGEMETS

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