Optimum Duty Cycle Evaluation for Slotted IEEE 802.15.4 Mac for Real Time Applications

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Abstract— Wireless Sensor Networks (WSNs) have been attracting increasing interest for supporting a new generation of ubiquitous computing systems with great potential for many applications such as surveillance, environmental monitoring, health care monitoring or home automation. Sensors and wireless sensor networks are being deployed around the world, measuring local and global environmental conditions. Their advanced sensing functionalities enable context-aware ubiquitous platforms, middleware and applications to proliferate. Recent advances in micro-electro-mechanical systems technology, wireless communications, and digital electronics have enabled the development of low-cost, low-power, multi-functional sensor nodes that are small in size and communicate over short distances. Low-rate low-power consumption and low-cost communication are the key points which are associate with wireless sensor networks and that lead to the specification of the IEEE 802.15.4 standard for WSN. Nevertheless, when addressing applications with (soft/hard) timing requirements some inherent paradoxes emerge, such as power-efficiency versus timeliness. Consequently, there is the need of engineering solutions for an efficient deployment of IEEE 802.15.4 in such scenarios. The current specification of the IEEE 802.15.4 standard for beacon-enabled wireless sensor networks does not define how the fraction of the time that wireless nodes are active, known as the duty cycle, needs to be configured in order to achieve the optimal network performance in all traffic conditions. This paper proposed an optimal duty cycle decision mechanism that adapts the duty cycle during run time without the need of human intervention in order to minimize power consumption while balancing probability of successful data delivery and delay constraints of the application.

Key words: Wireless Sensor Networks, Real time Systems, Energy Consumption, Duty Cycle, Throughput, Stochastic Modeling

I. INTRODUCTION

Low-cost, low power, multifunctional sensor nodes that are small in size and communicate over short distances have been developed due to the recent advances in micro-electro-mechanical systems (MEMS) and wireless communication [1]. These tiny sensors have the ability of sensing, data processing, and communicating with each other. Wireless Sensor Networks (WSN) [2] which rely on collaborative work of large number of sensors are realized. Sensor nodes can be used within many deployment scenarios such as continuous sensing, event detection, event identification, location sensing, and local control of actuators for a wide range of applications such as military, environment, health, space exploration, and disaster relief [3]. Although a large volume of research has been performed and some algorithms are proposed, there is ongoing research on this subject in recent years. One of the challenging subjects and design constraints in WSNs is efficient energy consumption [4]. Since a sensor node is a microelectronic device, it can only be equipped with a limited power source (<0.5 Ah, 1.2 V). In most application scenarios, replenishment of power resources might be impossible or infeasible [4]. Moreover, each node plays the dual role of data originator and data router, in multi-hop sensor networks [5], therefore malfunction of nodes can cause serious problems in the sensor network. Furthermore, most of the application based on long time monitoring directly affects the network efficacy and usefulness. Main sources of power dissipation are used during data processing, data transmission, data reception and idle listening. The power consumed during transmission is the greatest portion of energy consumption of any node. Considering the limited capabilities and vulnerable nature of an individual sensor, a wireless sensor network has a large number of sensors deployed in high density (high up to 20nodes/m3). Since the nodes are deployed densely and in an ad-hoc fashion, many nodes stay inactive for long periods and idle listening power dissipation becomes significant. Therefore these nodes can be considered as redundant and can be put to sleep [6]. The main idea will be scheduling sensors to work alternatively and the system lifetime will be prolonged correspondingly.

A. *Problem Statement*

IEEE 802.15.4 defines a standard for networks of low-power sensors and actuators with two operating modes. The first one is the non-beacon enabled mode [7] in which receivers need to be awake to receive a frame at any time. This mode does not enable low energy consumption in multichip topologies. The second mode, beacon-enabled [8], defines super frames that start with the transmission of beacons sent by coordinators. Nodes associated with a coordinator contend for channel access according to a slotted CSMA/CA [8] scheme during the active period at the beginning of the super frame. Long lifetimes are possible with low duty cycles [9], nodes are only awake during a small part of a super frame and they sleep most of the time.

When IEEE 802.15.4 operates with the default parameters defined by the standard in the beacon-enabled mode, any significant traffic causes frequent collisions and packet losses, which further leads to increased energy consumption and low throughput. Low duty cycles even exacerbate the problem, because more nodes become active after long periods of sleep and contend for channel access. So, operating IEEE 802.15.4 with low duty cycles requires a mechanism for adapting the MAC parameters to obtain low energy consumption and efficient operation during active periods at the same time. Optimizing the throughput becomes important in 802.15.4 networks with low duty cycles, because the nominal bit rate of 250 kb/s is proportionally reduced to the duration of the active period with respect to the super frame size and is shared by all active nodes associated with the same coordinator.

B. Motivation

The cellular network [10] was a natural extension of the wired telephony network that became pervasive during the mid-20th century. As the need for mobility and the cost of laying new wires increased, the motivation for a personal connection independent of location to that network also increased. A major concern in WSN is energy conservation, since battery-powered sensor nodes are expected to operate autonomously for a long time, e.g., for months or even years. Another critical aspect of WSN is reliability, which is highly application-dependent. In most cases it is possible to trade-off energy consumption and reliability in order to prolong the network lifetime, while satisfying the application requirements. Coverage of large area is provided through (1-2km) cells that cooperate with their neighbors to create a seemingly seamless network. Examples of standards are GSM, IS-136, IS-95. Cellular standards basically aimed at facilitating voice communications throughout a metropolitan area. During the mid-1980s, it turned out that an even smaller coverage area is needed for higher user densities and the emergent data traffic. The IEEE 802.11 working group for WLANs is formed to create a wireless local area network standard. IEEE 802.15.4 defines a popular MAC standard for wireless sensor and actuator networks. With the default parameters, under medium to high load, 802.15.4 generates excessive collisions and packet losses. Low duty cycles even exacerbate the problem, because more nodes become active after long periods of sleep and contend for channel access. This paper is organized as follows:

Section 1 presents an overview of the subject matter and gives the problem statement and the approach for the research. Section 2 provides the research approach. Section 3 presents the proposed technique for evaluation of optimal duty cycles. Section 4 gives the simulation results and the plots for various values of network parameters. Section 5 concludes the paper.

II. RESEARCH APPROACH

In this paper, the behaviour of IEEE 802.15.4 in the beacon-enabled mode is analyzed to identify the main performance bottlenecks and apply the optimization approach of the 802.11 Idle Sense. However, a simple application of the Idle Sense optimization approach is insufficient, because bursts of traffic that may arise at the beginning of the active period require special handling. Moreover, the contrast between the behaviours of the coordinator and the nodes that turn on their radios as rarely as possible leads to a specific contention control protocol. Assuming a Personal Area Network (PAN) [11] of n nodes with a single coordinator (the star topology), the optimum duty cycle is analyzed depending on traffic bursts and specified data rates. A stochastic model is developed for the network and the model is validated through simulations and shown to be in excellent agreement. The simulation is done using OmNET++ [12] network simulation and results are analyzed and compared with the standard IEEE 802.15.4 specifications.

III. PROPOSED WORK

A. Analytical Description of Optimum Duty Cycle for Slotted IEEE 802.15.4

Consider a LR-PAN implemented using slotted IEEE 802.15.4 MAC consisting of n nodes, with contention free period (CFP) in the superframe structure. The active period, known as superframe duration is given by

$SD = aBaseSuperFrameDuration*2^{SO}$ symbols

The complete duration between two beacons, the beacon interval, is given by

$BI = aBaseSuperFrameDuration*2^{BO}$ symbols

The parameter BO is called macBeaconOrder and it is restricted by $0 \leq BO \leq 14$. The parameter SO is called macSuperFrameOrder and it is restricted by $0 \leq SO \leq BO \leq 14$.

The aBaseSuperframeDuration constant denotes the minimum length of the superframe when BO is equal to 0. The standard fixes this duration to 960 symbols (one symbol corresponds to 4 bits, assuming the 2.4 GHz frequency band and 250 kbps of bit rate).. The maximum number of GTS that can be allocated to the superframe is 7. The allocation of the GTS cannot reduce the length of the CAP to less than aMinCAPLength (440 symbols). The active period of the superframe is divided in 16 equal time slots. The length of each slot is equal to $aBaseSlotDuration*2^{SO}$ symbols, where aBaseSlotDuration is the minimum number of symbols in a slot and equal to 60 symbols. One Superframe Duration = 16 slots, among which maximum 7 GTS are permissible.

When both BO =SO=15, the superframe is fully active and provides no sleep period for nodes. This leads to complete synchronization of coordinator and the clients, however, by consuming the maximum power.

The beacon signal is sent to all the nodes which constitutes the network. Also, all the devices having data to sent to the PAN coordinator may compete to send the data in the Contention Access Period and also for a GTS in case of real time data transfer. The GTS slot is provided to a device in the subsequent superframe on demand and the information regarding the same in contained in the beacon signal. The maximum number of GTS that can be allocated in a superframe is 7.

The transmission time is referred to as the time it takes for sender to put all the bits of the frame on the transmission line. The propagation delay is the delay it takes for the single bit of the frame to reach its destination from source. It is assumed that all the nodes in the network have fixed frame size having transmission time T. Let the mean number of frames sent per frame transmission time be λ. This mean number of frames include all those frames which are retransmitted due to collisions under heavy. In case of light load, the transmitted population comprises mostly of fresh packets whereas under heavy load, the number of retransmitted packets (packets for which ack is not received) may even exceed fresh packets

Under no network policy, without using any collision avoidance and collision detection and without any back-off time or contention window, assuming that λ is the mean number frames (fresh and retransmitted) generated per unit time, according to Poisson Probability Distribution.

The vulnerable period is the period in which there is a possibility of collision, which in case of slotted time is equal to T.

The probability of k transmissions per transmission time, is given by the definition of Poisson Distribution

$$P_k = \frac{\lambda^k * e^{-\lambda}}{k!} \qquad eq.3.1$$

The probability of 0 transmissions during the vulnerable period is:

$$P_{k=0} = e^{-\lambda} \qquad eq\ 3.2$$

The Throughput (S) of the system is defined as:

S = [mean number of packets transmitted per unit time]*$P_{k=0}$

giving

$$S = \lambda e^{-\lambda} \qquad eq.3.3$$

which is illustrated in Figure 3.1

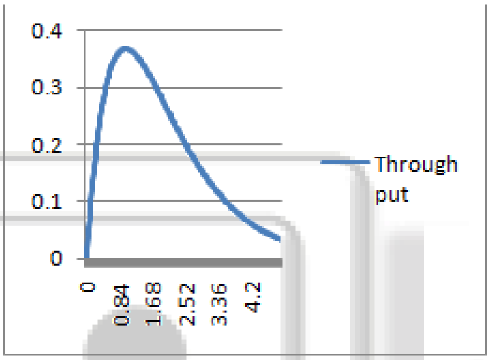

Fig. 3.1 Throughput Analysis without any back off and Contention window

As depicted from the above figure, the throughput reaches the maximum value when λ = 1 which can be derived from the equation given above:

$$\frac{dS}{d\lambda} = e^{-\lambda} - \lambda * e^{-\lambda} = 0 \qquad eq.3.4$$

for maxima or minima.

Solving for λ gives λ =1 in accordance with Figure 3.1 given above.

Throughput analysis for CAP of IEEE 802.15.4 with CSMA/CA in star topology network is a complex problem and requires stochastic modeling due to random backoff period.

Consider a network with N nodes and a single PAN coordinator. Each of the nodes send data to the PAN coordinator according to Poisson Distribution in the CAP or may request for GTS time slots. The information regarding GTS allocation is broadcasted to all the nodes through network beacons.

Consider the following parameter specifications for the performance model as shown in table 3.1 below.

Parameter	Description
λ_D	Mean number of data packets sent during CAP
λ_G	Mean number of GTS requests received during one CAP
T	Maximum Permissible delay for Time Critical Data Packets
T_S	Inactive Period
GTS_{MAX} (= 7)	Maximum number of GTS allowed in the superframe in view of the current number of GTS requests. The upper threshold being 7.

Table 3.1: Parameter And Description For Mathematical Model Of Superframe For Duty Cycle Analysis

B. *Markov model [28] of the system*

The proposed Markov model gives the system modeling with N nodes and a PAN coordinator. Let t be the time period as the time progresses, expressed in superframe units. Thus, t is a superframe counter. t also corresponds to network time due to beacon enabled mode. The superframe counter t = 1 correspond to the first superframe of the network without any waiting requests at the PANC.

Let λ_i be the probability of i successful requests during CAP, given that the maximum number of requests is L_{max}. If the arriving requests observe that the queue size of already waiting requests is over a threshold B_{MAX} , then these arriving requests are dropped because of the time limitation N_{GPT}.

B_{MAX} is fixed and is given by 7*(N_{GPT} + 1), where N_{GPT} = aGTSDescPersistanceTime. After N_{GPT} , the GTS description of beacon is removed. When there are k requests, where $7 \leq k \leq B_{MAX}$, then some requests k-7, will be delayed to obtain GTS in the next time slot.

One relation that can be derived from the mean values is that the incoming packets to the PAN coordinator during CAP comprises of data as well as GTS requests

$$\lambda_i = \lambda_D + \lambda_G \qquad eq.3.5$$

Assuming Poisson Probability Distribution for GTS requests, the probability of k requests during a CAP is given by:

$$P_k = \frac{{\lambda_G}^k * e^{-\lambda_G}}{k!} \qquad eq.3.6$$

The maximum number of GTS requests in one super frame is limited by B_{MAX} (=7). Considering the worst case GTS allotment corresponding to N_{GPT}. In this case, a GTS request which reaches the PAN coordinator with be allocated a GTS frame in #N_{GPT} super frame, probably at the end of the GTS time slot. The super frame duration is given by:

SD = aBaseSuperframeDuration ×2^{SO}
and
BI= aBaseSuperframeDuration ×2^{BO}

Let the Inactive Period is denoted by
IP = aBaseSuperframeDuration ×2^{IO}

The worst case delay suffered by a GTS request is, therefore
T_{MAX} = BI*(N_{GPT}+1)
or
T_{MAX} = (SD +IP) *(N_{GPT}+1)
T_{MAX} = aBaseSuperframeDuration (2^{SO} +2^{IO}) *(N_{GPT}+1)

Optimal values of BO, and SO can be derived for given traffic types and acceptable values of T_{MAX}. Section 4 gives the results and plots for different values of model parameters.

IV. ANALYSIS OF PROPOSED WORK

A. Superframe Structure based on SO and BO

The superframe order and the beacon order are the most important parameters in setting up a wireless sensor network in energy efficient mode.

The standard parameters for the network are given by;

BI = aBaseSuperframeDuration × 2^{BO}

SD = aBaseSuperframeDuration × 2^{SO}

The sleep interval of the nodes is the period in which the node goes to an inactive state thereby saving its battery life. The inactive duration is given by

Inactive Period = aBaseSuperframeDuration*(2^{BO} - 2^{SO})

Also, $1 \leq SO \leq BO \leq 14$,

The following illustrative example can show the parameter specifications and corresponding values of other parameters for any superframe structure for a network.

Parameter	**Value**	**Remarks**
Frequency	2.4 GHz Frequency Band	-
Data rate	250 kbps	-
Baud Rate	4bits/symbol	-
BO	12 (example value)	Beacon Order
SO	6 (example value)	SuperFrame Order
aBaseSuperframeDuration	960 symbols (specified in IEEE 802.15.4)	
BI	3932160 symbols = aBaseSuperframeDuration*2^{BO} = 62914.56 ms	Beacon Interval = Time Gap between Beacon signals
SD	61440 symbols = aBaseSuperframeDuration*2^{SO} = 983.04 ms	Beacon Interval = Time interval of CAP plus CFP. Each SD is divided into 16 equal slots.
aBaseSlotDuration	60 symbols (min value as specified in IEEE 802.15.4) = 0.96 ms	
aBaseSlotDuration (For current values of BO and SO)	=SD/16 = aBaseSlotDuration*2^{SO} = 3840 symbols = 61.44 ms	
Inactive Period Per SuperFrame	91931.52 ms	

Table 4.1: Example Illustration For A Supertrame Structure

One can have the following trend for sleep time distribution.

abaseSuperframeDuration =				0.0001 sec	Worst case Max Delay For time Critical Packet			
Count of GTS persistance Time (#Superframe)					2	3	4	5
BO	SO	Active Period	Inactive Period	Total Period				
5	2	0.0004	0.0028	0.0032	0.0096	0.0128	0.016	0.0192
5	3	0.0008	0.0024	0.0032	0.0096	0.0128	0.016	0.0192
5	4	0.0016	0.0016	0.0032	0.0096	0.0128	0.016	0.0192
6	2	0.0004	0.006	0.0064	0.0192	0.0256	0.032	0.0384
6	3	0.0008	0.0056	0.0064	0.0192	0.0256	0.032	0.0384
6	4	0.0016	0.0048	0.0064	0.0192	0.0256	0.032	0.0384
6	5	0.0032	0.0032	0.0064	0.0192	0.0256	0.032	0.0384
7	2	0.0004	0.0124	0.0128	0.0384	0.0512	0.064	0.0768
7	3	0.0008	0.012	0.0128	0.0384	0.0512	0.064	0.0768
7	4	0.0016	0.0112	0.0128	0.0384	0.0512	0.064	0.0768
7	5	0.0032	0.0096	0.0128	0.0384	0.0512	0.064	0.0768
7	6	0.0064	0.0064	0.0128	0.0384	0.0512	0.064	0.0768
8	2	0.0004	0.0252	0.0256	0.0768	0.1024	0.128	0.1536
8	3	0.0008	0.0248	0.0256	0.0768	0.1024	0.128	0.1536
8	4	0.0016	0.024	0.0256	0.0768	0.1024	0.128	0.1536
8	5	0.0032	0.0224	0.0256	0.0768	0.1024	0.128	0.1536
8	6	0.0064	0.0192	0.0256	0.0768	0.1024	0.128	0.1536
8	7	0.0128	0.0128	0.0256	0.0768	0.1024	0.128	0.1536
9	1	0.0002	0.051	0.0512	0.1536	0.2048	0.256	0.3072
9	2	0.0004	0.0508	0.0512	0.1536	0.2048	0.256	0.3072
9	3	0.0008	0.0504	0.0512	0.1536	0.2048	0.256	0.3072
9	4	0.0016	0.0496	0.0512	0.1536	0.2048	0.256	0.3072
9	5	0.0032	0.048	0.0512	0.1536	0.2048	0.256	0.3072
9	6	0.0064	0.0448	0.0512	0.1536	0.2048	0.256	0.3072
9	7	0.0128	0.0384	0.0512	0.1536	0.2048	0.256	0.3072
9	8	0.0256	0.0256	0.0512	0.1536	0.2048	0.256	0.3072
10	1	0.0002	0.1022	0.1024	0.3072	0.4096	0.512	0.6144
10	2	0.0004	0.102	0.1024	0.3072	0.4096	0.512	0.6144
10	3	0.0008	0.1016	0.1024	0.3072	0.4096	0.512	0.6144
10	4	0.0016	0.1008	0.1024	0.3072	0.4096	0.512	0.6144

10	5	0.0032	0.0992	0.1024	0.3072	0.4096	0.512	0.6144
10	6	0.0064	0.096	0.1024	0.3072	0.4096	0.512	0.6144
10	7	0.0128	0.0896	0.1024	0.3072	0.4096	0.512	0.6144
10	8	0.0256	0.0768	0.1024	0.3072	0.4096	0.512	0.6144
10	9	0.0512	0.0512	0.1024	0.3072	0.4096	0.512	0.6144
11	1	0.0002	0.2046	0.2048	0.6144	0.8192	1.024	1.2288
11	2	0.0004	0.2044	0.2048	0.6144	0.8192	1.024	1.2288
11	3	0.0008	0.204	0.2048	0.6144	0.8192	1.024	1.2288
11	4	0.0016	0.2032	0.2048	0.6144	0.8192	1.024	1.2288
11	5	0.0032	0.2016	0.2048	0.6144	0.8192	1.024	1.2288
11	6	0.0064	0.1984	0.2048	0.6144	0.8192	1.024	1.2288
11	7	0.0128	0.192	0.2048	0.6144	0.8192	1.024	1.2288
11	8	0.0256	0.1792	0.2048	0.6144	0.8192	1.024	1.2288
11	9	0.0512	0.1536	0.2048	0.6144	0.8192	1.024	1.2288
11	10	0.1024	0.1024	0.2048	0.6144	0.8192	1.024	1.2288
12	1	0.0002	0.4094	0.4096	1.2288	1.6384	2.048	2.4576
12	2	0.0004	0.4092	0.4096	1.2288	1.6384	2.048	2.4576
12	3	0.0008	0.4088	0.4096	1.2288	1.6384	2.048	2.4576
12	4	0.0016	0.408	0.4096	1.2288	1.6384	2.048	2.4576
12	5	0.0032	0.4064	0.4096	1.2288	1.6384	2.048	2.4576
12	6	0.0064	0.4032	0.4096	1.2288	1.6384	2.048	2.4576
12	7	0.0128	0.3968	0.4096	1.2288	1.6384	2.048	2.4576
12	8	0.0256	0.384	0.4096	1.2288	1.6384	2.048	2.4576
12	9	0.0512	0.3584	0.4096	1.2288	1.6384	2.048	2.4576
12	10	0.1024	0.3072	0.4096	1.2288	1.6384	2.048	2.4576
12	11	0.2048	0.2048	0.4096	1.2288	1.6384	2.048	2.4576
13	1	0.0002	0.819	0.8192	2.4576	3.2768	4.096	4.9152
13	2	0.0004	0.8188	0.8192	2.4576	3.2768	4.096	4.9152
13	3	0.0008	0.8184	0.8192	2.4576	3.2768	4.096	4.9152
13	4	0.0016	0.8176	0.8192	2.4576	3.2768	4.096	4.9152
13	5	0.0032	0.816	0.8192	2.4576	3.2768	4.096	4.9152
13	6	0.0064	0.8128	0.8192	2.4576	3.2768	4.096	4.9152
13	7	0.0128	0.8064	0.8192	2.4576	3.2768	4.096	4.9152
13	8	0.0256	0.7936	0.8192	2.4576	3.2768	4.096	4.9152
13	9	0.0512	0.768	0.8192	2.4576	3.2768	4.096	4.9152
13	10	0.1024	0.7168	0.8192	2.4576	3.2768	4.096	4.9152
13	11	0.2048	0.6144	0.8192	2.4576	3.2768	4.096	4.9152
13	12	0.4096	0.4096	0.8192	2.4576	3.2768	4.096	4.9152
14	1	0.0002	1.6382	1.6384	4.9152	6.5536	8.192	9.8304
14	2	0.0004	1.638	1.6384	4.9152	6.5536	8.192	9.8304
14	3	0.0008	1.6376	1.6384	4.9152	6.5536	8.192	9.8304
14	4	0.0016	1.6368	1.6384	4.9152	6.5536	8.192	9.8304
14	5	0.0032	1.6352	1.6384	4.9152	6.5536	8.192	9.8304
14	6	0.0064	1.632	1.6384	4.9152	6.5536	8.192	9.8304
14	7	0.0128	1.6256	1.6384	4.9152	6.5536	8.192	9.8304
14	8	0.0256	1.6128	1.6384	4.9152	6.5536	8.192	9.8304
14	9	0.0512	1.5872	1.6384	4.9152	6.5536	8.192	9.8304
14	10	0.1024	1.536	1.6384	4.9152	6.5536	8.192	9.8304
14	11	0.2048	1.4336	1.6384	4.9152	6.5536	8.192	9.8304
14	12	0.4096	1.2288	1.6384	4.9152	6.5536	8.192	9.8304
14	13	0.8192	0.8192	1.6384	4.9152	6.5536	8.192	9.8304

Table 4.2: Worst Case Max Delay Analysis For Data Packets

The following table gives various values of delay with BO, SO, L_{MAX} and aBaseSuperFrameDuration parameters. However, the table is difficult to plot with these discrete values.

The schematic plots for various parameters as per the table are shown below. The Horizontal scale shows the values of SO while the vertical axis shows the time (in seconds).

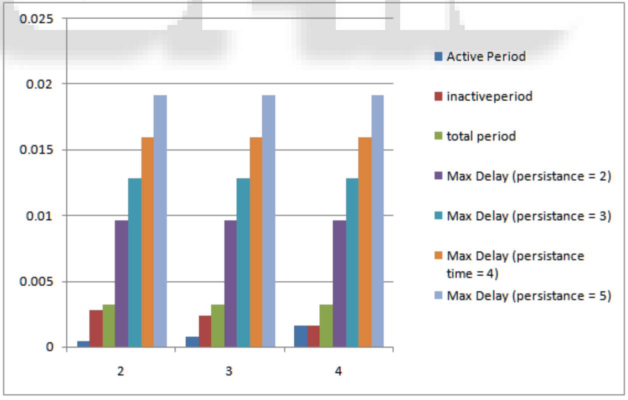

Fig. 4.1: Graphical Illustration of various parameters for QoS for BO=5 (Horizontal axis shows SO and vertical axis shows time)

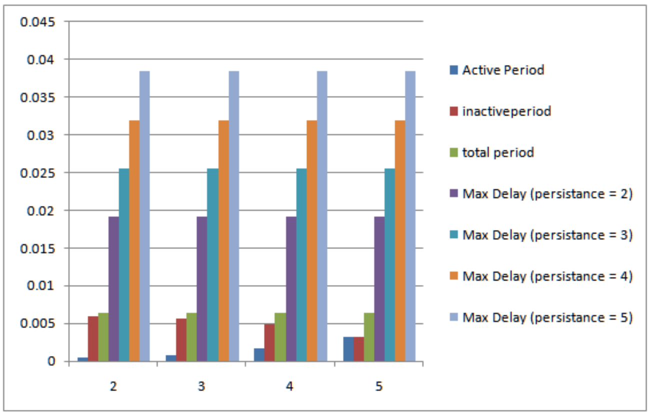

Fig. 4.2: Graphical Illustration of various parameters for QoS for BO=6 (Horizontal axis shows SO and vertical axis shows time)

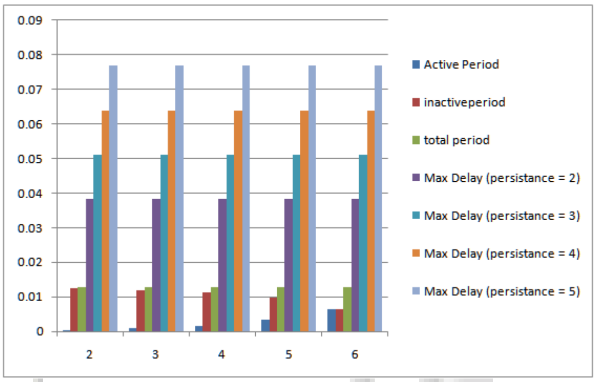

Fig. 4.3: Graphical Illustration of various parameters for QoS for BO=7 (Horizontal axis shows SO and vertical axis shows time)

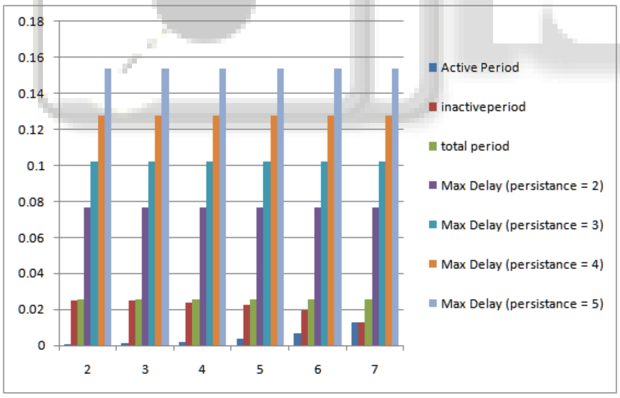

Fig. 4.4: Graphical Illustration of various parameters for QoS for BO=8 (Horizontal axis shows SO and vertical axis shows time)

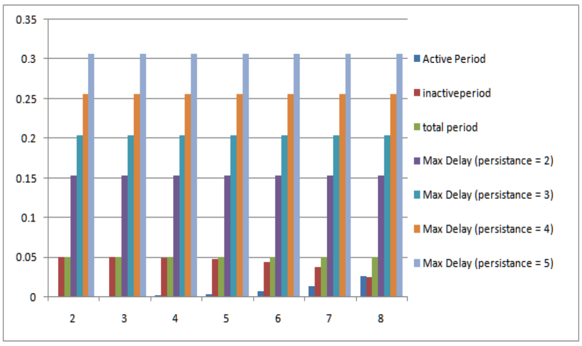

Fig. 4.5: Graphical Illustration of various parameters for QoS for BO=9 (Horizontal axis shows SO and vertical axis shows time)

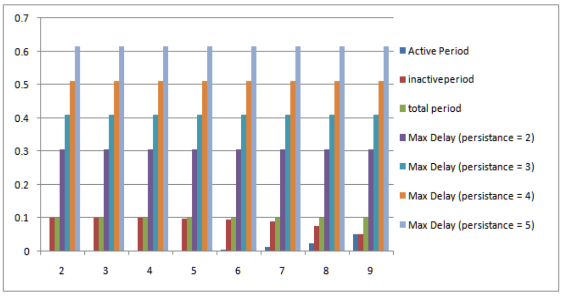

Fig. 4.6: Graphical Illustration of various parameters for QoS for BO=10 (Horizontal axis shows SO and vertical axis shows time)

One can set a specific limit on the worst case time delay in case of time sensitive GTS packets and can choose the BO, and SO values accordingly.

B. Optimum Duty Cycle Analysis

As mentioned previously, the duty cycle is the fraction of time of entire beacon interval in which the node is active. The duty cycle can be computed as:

$$Duty\ Cycle = \frac{2^{SO}}{2^{BO}} = 2^{SO-BO} \qquad eq.4.1$$

for the most optimal value of BO and SO provided T_{MAX} (the maximum transmission time) is below threshold limits. The optimum value of DC depends upon SO and BO. However, the value SO depends upon the network topology and the number of nodes in the network and the traffic rates, depending upon the type of implementation. The value T_{MAX} is the most important parameter of QoS and is therefore directly proportional to the Duty Cycle.

C. Battery life dependency on Duty Cycle:

The gain in battery life can be computed in a simple manner. Suppose the battery life in a node which is working continuously without any sleep mode is n times active period. However, this is coupled by n times inactive period and is given by:

$$\text{Gain in Battery Life} \\ = \text{n} * \text{aBaseSuperFrameDuration} * 2^{\text{BO}} \\ - \text{n} * \text{aBaseSuperFrameDuration} * 2^{\text{BO}}$$

Thus

$$Gain\ in\ Battery\ Life \\ = n * aBaseSuperFrameDuration \\ * (2^{BO} - 2^{BO})$$

Assuming that a single lithium-ion pencil battery can work for 2 hrs without any interruption in a sensor node, one can get the following values for the battery life:

BO	SO	Active Period	Inactive Period	Total Period	Energy Consumed	Time Taken	1.6 volt will be consumed in (months)
14	1	0.0002	1.6382	1.6384	4.44E-08	1.6384	22.75556
14	2	0.0004	1.638	1.6384	8.89E-08	1.6384	11.37778
14	3	0.0008	1.6376	1.6384	1.78E-07	1.6384	5.688889

14	4	0.0016	1.6368	1.6384	3.56E-07	1.6384	2.844444
14	5	0.0032	1.6352	1.6384	7.11E-07	1.6384	1.422222
14	6	0.0064	1.632	1.6384	1.42E-06	1.6384	0.711111
14	7	0.0128	1.6256	1.6384	2.84E-06	1.6384	0.355556
14	8	0.0256	1.6128	1.6384	5.69E-06	1.6384	0.177778
14	9	0.0512	1.5872	1.6384	1.14E-05	1.6384	0.088889
14	10	0.1024	1.536	1.6384	2.28E-05	1.6384	0.044444
14	11	0.2048	1.4336	1.6384	4.55E-05	1.6384	0.022222
14	12	0.4096	1.2288	1.6384	9.1E-05	1.6384	0.011111
14	13	0.8192	0.8192	1.6384	0.000182	1.6384	0.005556

Table 4.3: Gain In Battery Life For Various Settings Of Bo And So

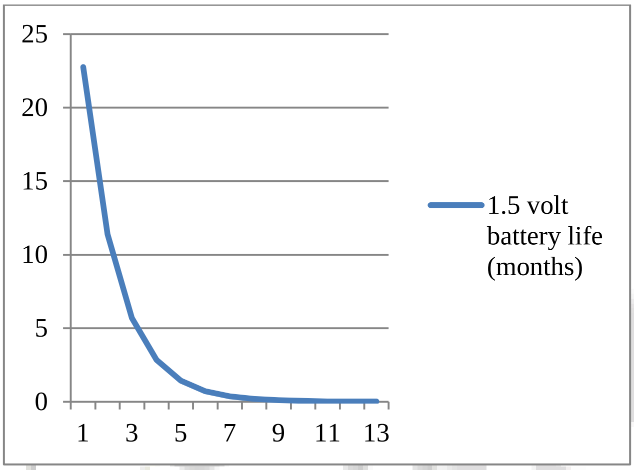

Fig. 4.7: Battery life dependency on Superframe Order.

Horizontal scale shows SO, vertical scale shows Months

The above trend is obtained by assuming that the sensor node consumes no battery power in inactive state. However, this does not happen in actual practice. Still, battery life for about 6 months of a single lithium-ion batteries has already been achieved with current sensor nodes and sleep-wake-up mechanisms of IEEE 802.15.4

The above plot clearly indicates that with the increase in SO (horizontal scale) from 1 to 12, the battery life decreases tremendously. This is consistent with the characteristic that SO is a measure of the active period (contention access period and GTS) and hence the node is continuously active for the entire duration before going into the sleep mode. Section 5 discusses the results and conclude the paper.

V. CONCLUSION AND FUTURE SCOPE

In this paper, the new IEEE 802.15.4 MAC standard for low-rate low-power wireless networks, with a focus on the beacon-enabled MAC for star-topology networks is described. Based on OmNET++ simulations, the performance of various features in the IEEE 802.15.4 MAC is evaluated. It is found that extremely low duty cycle operation enables significant energy saving, but that these savings can come at the cost of significantly higher latency and lower bandwidth. The CSMA-CA algorithm reduces energy cost due to idle listening in the backoff period but increases the collision at higher rate and larger number of sources. While the use of GTS in the contention-free period can allow dedicated bandwidth to a device to ensure low latency, the device need to track the beacon frames in this mode, which increases the energy cost. The worst time delivery of packets is analyzed and showed that this depends upon the duty cycle and data rate. One direction for future work would be to employ real experiments to test the performance of IEEE 802.15.4 when products become available. Another is to evaluate the performance of this protocol in peer-to-peer topologies.

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