ISSN:0975-9646
Alladi Ramesh et al, / (IJCSIT) International Journal of Computer Science and Information Technologies, Vol. 3 (2) , 2012,3382-3387

Analyzing the Performance of GTS Allocation Using Markov Model in IEEE 802.15.4

Alladi Ramesh[1],Dr.P.Sumithabhashini[2]
[1]*Dept.of CSE, PETW, Hyderabad*
[2] *Dept.of ECE, PETW, Hyderabad*

Abstract-**In this paper, we present an analytical model based on a Markov chain to compute the performance of the GTS allocation mechanism in IEEE 802.15.4 standard. In this, theoretical analysis gives accurate numerical results, by using the network calculus. We evaluate the stability of the queue size at the network coordinator, the delay to serve a GTS request, and to achieve throughput for different traffic patterns and protocol parameters. We derive the dependence of the average delay and queue size as a function of the number of requests. Furthermore, we analyze to achieve throughput as a function of the amount of data packets to forward for each request. We observe the lower beacon order which will give lower delay. By contrast, higher beacon order increases significantly the average delay and degrades the throughput due to wasted bandwidth. Monte Carlo simulations are used for the analysis, which shows that the theoretical analysis is quite accurate. Thus, our analysis can be used to design efficient GTS allocation for IEEE 802.15.4.**

Keywords: IEEE 802.15.4 standard, GTS allocation, Wireless Sensor Network, MAC, Markov Chain.

I. INTRODUCTION

To support time-critical applications, IEEE 802.15.4 offers a guaranteed time slot (GTS) allocation mechanism at the network coordinator. The primary goal of GTS allocation is providing communication services to time critical data, i.e., make certain guarantees on eventual delivery and delivery times of packets to be transmitted by local devices to the network coordinator. Specifically, in IEEE 802.15.4, packets are transmitted on a superframe basis (see Fig. 1).

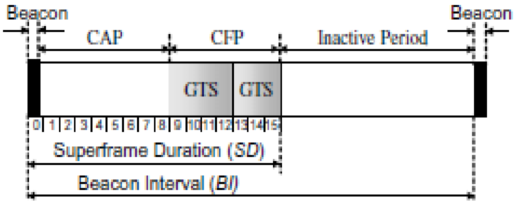


Fig. 1. Superframe structure in IEEE 802.15.4.

Each superframe is divided into Contention Access Period (CAP), where nodes contend among each other to send packets, and a Contention Free Period (CFP), where nodes have GTSs to send packets without contention and thus with guaranteed transmission [1]. Satisfactorily the CFP, where the GTS mechanism operates. Both CAP and CFP have been studied in [2] and [3], but the approach is mainly based on simulations. Some interesting algorithm are proposed to improve the performance of GTS allocation mechanism. To maximize the bandwidth utilization, the smaller slot size and offline message scheduling algorithm are proposed in [4], [5] and [6], respectively. In [7], the delay constraint and bandwidth utilization are considered to design the GTS scheduling algorithm. Huang [8] proposes an adaptive GTS allocation scheme by considering the low delay and fairness. An interesting theoretical performance evaluation of the GTS allocation has been proposed by Koubaa et al. [9], [10], [11] by using network calculus. These papers focus on the impact of the IEEE 802.15.4 standard parameters (the beacon and super frame orders [1]), the delay, throughput and energy consumption of GTS allocation. In [12], a round-robin scheduler is proposed to improve the bandwidth utilization based on network calculus approach. Network calculus, however, assumes a continuous flow model (whereas communication happens through low data rate packets in reality) and it analyzes the worst-case of traffic flows (which leads to severe under-utilization of time slots in actual environments). Consequently, the difference between the network flow model of the network calculus approach and the actual behavior may be quite large.

In this paper, we focus mainly on the uplink scenario, which is the most relevant for sensor networks application, and we develop a theoretical analysis of the impact of GTS allocation mechanism on stability, delay and throughput. More specifically, the original contributions of this paper are the following:

We present a Markov chain model to analyze the performance of GTS allocation mechanism for IEEE 802.15.4 in terms of stability and delay in the slot assignment, and throughput guaranteed. The stability analysis, which gives the queue overflow probability, is quite useful for understanding the stability of the queue size of the network coordinator. Furthermore, we derive these performance measures as explicit function of the number of requests arriving during the superframes and protocol parameters. We believe that our investigation is the first one to provide such an accurate modeling and performance analysis. As a result, our theoretical analysis can be effectively used to support efficiently real-time applications by the optimization of the GTS allocation.

The remainder of this paper is organized as follows. In section II, we describe an overview of IEEE 802.15.4. section III, we describe system model. In section IV, we propose a Markov chain modeling of the GTS allocation. In section V, we analyze the GTS stability, delay, and throughput. In section VI, we validate the theoretical analysis by simulations, and give performance of GTS allocation. Section VII concludes the paper.

II. AN OVERVIEW OF IEEE 802.15.4

Depending on the application requirements, IEEE 802.15.4 supports two topologies: the star topology and the peer-to-peer topology. In the star topology, communication links are established between wireless sensor nodes and a single centralized controller, called the PAN coordinator. The PAN coordinator is used to initiate, terminate or route flows in the network, where a node is either the initiation point or the termination point of a flow. Once the PAN coordinator gets started, it allows nodes to join its network and provides two types of medium access to these nodes. One is guaranteed and contention-free access and the other is contention-based access aligned with the boundaries of slots. All star networks operate independently from other star networks and all nodes in a star network are synchronized (slotted CSMA/CA). In a peer to- peer topology, each node is able to communicate with any other node within its transmission range. The PAN coordinator is chosen among these nodes. Once it is assigned, it allows only contention-based access (unslotted CSMA/CA).

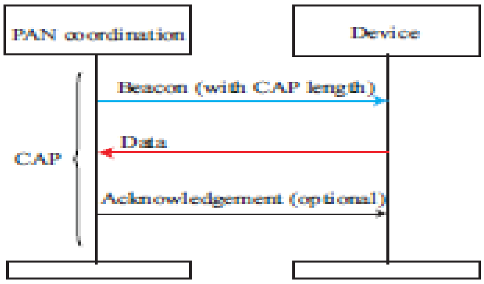
The MAC protocol in IEEE 802.15.4 operates in beacon mode and non-beacon mode. In the beacon mode, thePAN coordinator transfers the beacon frames periodically to all nodes within its radio coverage. All the nodes within the radio coverage are synchronized by these beacon frames. The non-beacon mode does not support time-sensitive applications since it allows only contention-based access through unslotted CSMA/CA. In addition, with no use of the beacons, all nodes in a wireless network are not synchronized. In the beacon mode, the PAN coordinator defines a superframe structure as depicted in Fig. 1. A superframe is bounded by two consecutive beacons and includes an active portion and an inactive portion. The active portion, which is divided into 16 slots, consists of a beacon, a contention access period (CAP) with a minimum length of seven slots and a contention free period (CFP) that contains at most seven guaranteed time slots (GTSs). During the CAP, devices use a slotted CSMA/CA mechanism for channel access. The GTSs in the CFP are allocated by the PAN coordinator to sensor nodes in the network for their communication needs.

III.SYSTEM MODEL

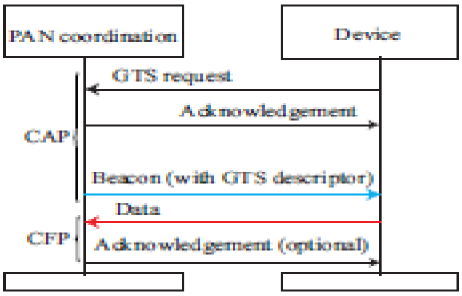
In this section we give an overview of the key points of IEEE 802.15.4 that are needed for our analysis. The IEEE 802.15.4 [1] standard specifies the physical layer and the MAC sub-layer for Low-Rate Wireless Personal Area Networks. The IEEE 802.15.4 supports beacon enabled and non-beacon enabled modes. The model selection is decided by the Personal Area Network coordinator (PANC). Fig. 1 shows a superframe structure of the beacon enabled mode. The PANC periodically sends the beacon frames in every beacon interval (BI) to identify its PAN and to synchronize devices that communicate with it. The PANC and devices can communicate during active period, called the superframe duration (SD), and enter the low-power mode during the inactive period. The structure of the superframe is defined by two parameters, the beacon order (BO) and the superframe order (SO), which determine the length of the superframe and its active period, respectively. The length of the superframe (BI) and the length of its active period (SD) are then defined as

$$\mathrm{BI} = aBaseSuperframeDuration \pounds 2^{BO}; \qquad (1)$$
$$\mathrm{SD} = aBaseSuperframeDuration \pounds 2^{SO}; \qquad (2)$$

where $0 \le SO \le BO \le 14$. The *aBaseSuperframeDuration* and *aBaseSlotDuration* denote the minimum length of the superframe and the number of symbols forming a superframe slot, when BO is equal to 0, respectively. The active period is divided into 16 equally sized time slots. Each active period can be further divided into a CAP and an optional CFP, composed of guaranteed time slots. The slotted or unslotted CSMA/CA is used within CAP dependent on the beacon enabled and non-beacon enabled mode, respectively. The GTS allocation mechanism of IEEE 802.15.4 deals only with the beacon enabled mode. Fig. 2(a) shows the data transmission during the CAP of beacon enabled mode. A slotted CSMA/CA mechanism is used to access the channel of non-time critical data frames and GTS requests during the CAP. In the CFP, the dedicated bandwidth is used for time critical data frames.



(a) Data transmission in CAP



(b) Data transmission during CFP.

Fig. 2. Data transfers during the CAP and CFP of beacon enabled PAN coordinator

Fig. 2(b) illustrates the GTS allocation mechanism within CFP of beacon enabled mode. The PANC is responsible for the GTS allocation and determines the length of the CFP in a superframe. To request the allocation of a new

GTS, the device sends the GTS request command to the PANC. The PANC confirms its receipt by ending an acknowledgment frame within CAP. Upon receiving a GTS allocation request, the PANC checks whether there are sufficient resources and, if possible, allocates the requested GTS. The GTS capacity in a superframe satisfies the following requirements:

1) The maximum number of GTSs to be allocated to devices is seven, provided there is sufficient capacity in the superframe.

2) The minimum length of a CAP is *aMinCAPLength*. Therefore the CFP length depends on the GTS requests and the current available capacity in the superframe.

In the following section, we propose an analytical modeling of the GTS allocation described above.

IV. MODELLING OF GTS ALLOCATION

Consider the IEEE 802.15.4 standard with a star network and a set of *N* nodes within the PANC's radio coverage.

Assume that the network operates in beacon enabled mode. Each device in the range of the PANC generates data packets to be sent to the PANC and informs the coordinator on the need of GTS resources by sending the request during CAP. Therefore, the PANC needs to allocate a number of GTSs by considering the received requests. These requests are stored in a queue of the PANC, and wait to be served in the next superframes, where the related GTS may be allocated. If too many requests arrive with respect to the PANC queue size, then we have a queue overflow. We consider only the transmit GTSs for the uplink traffic. Furthermore, we assume that all GTS transmissions are successful. Each device is allocated at most one GTS and the maximum number of GTSs *¢u* in a superframe is considered according to the IEEE 802.15.4 specifications [1].

The modeling of the GTS allocation is given in two steps.First, we derive the constraints on the number of time slots to allocate by considering the details of the GTS allocation mechanism of IEEE 802.15.4 specification. Then, we model the behavior of GTS allocation using Markov chain. Details follow in the sequel.

A. Number of Guaranteed Time Slots

In this , the number of GTSs that can be allocated as a function of IEEE 802.15.4 protocol parameters (BO, SO) and the number of time-critical data packets for each GTS request that can be served, and the maximum forward delay that a packet experiences to be transmitted in the GTS.

B. Markov Chain Model

Here a Markov model is used to study the behavior of the GTS allocation mechanism, see Fig. 3. Let *t* be a positive integer representing the time progress as expressed in superframe units. In other words, *t* is the superframe counter. Note that *t* corresponds to network time due to the beacon enabled mode. The superframe counter *t* = 1 correspond to the first superframe of the network without any waiting requests at the PANC.

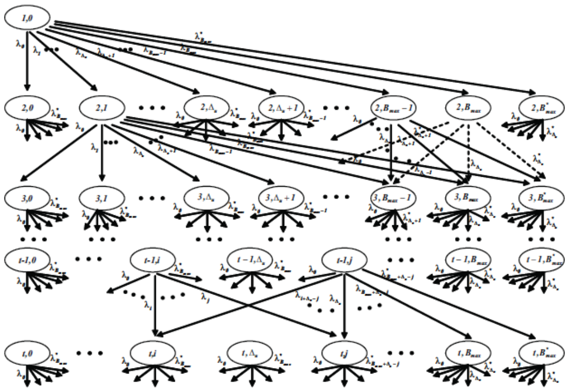


Fig. 3. Markov chain model for the GTS allocation of the CFP period

V.PERFORMANCE ANALYSIS OF GTS ALLOCATION

In this section, we build on the modeling of the GTS allocation developed in previous section by the Markov chain to analyze performance of GTS allocation in terms of stability (expected number of waiting and dropped requests, and queue overflow probability), delay of serving the requests, and throughput.

1. Stability Analysis

Here we give the expected number of GTSs requests by the devices waiting to be served, the expected number of GTSs requests that are dropped because of limited bandwidth, and the queue overflow probability.

Using the state probability *¼tk* of the Markov chain derived in the previous section, we can compute the mean number of waiting requests of the PANC at the superframe *t* by

$$\mathbb{E}\left[r(t)\right] = \sum_{k=0}^{B_{\max}} k\,\pi_k^t + B_{\max}\,\pi_{B_{\max}^*}^t \,. \tag{3}$$

Note that the number of requests is related to the delay of GTS allocation due to a FCFS fashion for the queue management. From the Markov chain model, we see that the expected number of dropped requests is given by

$$\begin{aligned}\mathbb{E}\left[r_d(t)\right] &= \sum_{i=0}^{\Delta_u-1} \pi_i^t \sum_{k=B_{\max}+1}^{L_{\max}} \lambda_k \left(k - B_{\max}\right) \\ &+ \sum_{i=\Delta_u}^{B_{\max}} \sum_{k=B_{\max}-i+\Delta_u+1}^{L_{\max}} \pi_i^t \lambda_k \left(k - \left(B_{\max} - i + \Delta_u\right)\right) \\ &+ \pi_{B_{\max}^*}^t \sum_{k=\Delta_u+1}^{L_{\max}} \lambda_k \left(k - \Delta_u\right) .\end{aligned} \qquad \ldots\ldots.(4)$$

Let *Pt*+1over denote the queue overflow probability of the requests in the superframe *t* + 1. Then

$$\begin{aligned}P_{\text{over}}^{t+1} &= \sum_{i=0}^{\Delta_u-1} \pi_i^t \sum_{k=B_{\max}+1}^{L_{\max}} \lambda_k + \sum_{i=\Delta_u}^{B_{\max}} \sum_{k=B_{\max}-i+\Delta_u+1}^{L_{\max}} \pi_i^t \lambda_k \\ &+ \pi_{B_{\max}^*}^t \sum_{k=\Delta_u+1}^{L_{\max}} \lambda_k \\ &= \sum_{i=0}^{\Delta_u-1} \pi_i^t \lambda_{B_{\max}}^* + \sum_{i=\Delta_u}^{B_{\max}} \pi_i^t \lambda_{B_{\max}-i+\Delta_u}^* + \pi_{B_{\max}^*}^t \lambda_{\Delta_u}^* .\end{aligned} \qquad ..\ (5)$$

Finally, to analyze the stability of GTS allocation, we can use the stationary distribution to derive the limit as *t* tends to infinity of the expected number of waiting requests, the expected number of dropped requests, and the queue overflow probability.

2.Delay Analysis

In this subsection, we analyze the expected delay of GTS allocation, namely the average delay between the arrival of a new request for GTSs by a device for a time-critical packet and its effective allocation in some of the next superframes The PANC determines a device list for GTS allocation in the next superframe based on a FCFS fashion. When *new requests* are received in a CAP, then the delay of GTS allocation can be estimated by observing the queue size of waiting requests. Note that PANC makes a preliminary decision whether it is able to serve a request or not. Assume that the arrival process of requests is uniformly distributed during CAP. Hence, the mean delay between the arrival time in CAP and the end of CAP at a superframe is half of CAP period.

The expected delay experienced by *j new requests* arriving at superframe *t* is

$$\begin{aligned}\mathbb{E}[D(t)] = &\sum_{i=0}^{\Delta_u-1}\sum_{j=1}^{L_{\max}} \pi_i^t \frac{\lambda_j}{\sum_{k=1}^{L_{\max}}\lambda_k}\{D_{i,j,t}\,u(B_{\max}-j)\\ &+D_{i,B_{\max},t}\,u(j-(B_{\max}+1))\}\\ &+\sum_{i=\Delta_u}^{B_{\max}}\sum_{j=1}^{L_{\max}} \pi_i^t \frac{\lambda_j}{\sum_{k=1}^{L_{\max}}\lambda_k}\{D_{i,j,t}\,u(B_{\max}-i+\Delta_u-j)\\ &+D_{i,B_{\max}-i+\Delta_u,t}\,u(j-(B_{\max}-i+\Delta_u+1))\}\\ &+\pi_{B_{\max}^*}^t\sum_{j=1}^{L_{\max}}\frac{\lambda_j}{\sum_{k=1}^{L_{\max}}\lambda_k}\{D_{B_{\max},j,t}\,u(\Delta_u-j)\\ &+D_{B_{\max},\Delta_u,t}\,u(j-(\Delta_u+1))\}\ , \qquad ..(6)\end{aligned}$$

where $D_{i;j;t}$ is the estimated delay and $L_{\max}$ is the maximum number of requests.

The average delay mainly depends on the traffic pattern ¸λi of the number of GTS requests and protocol parameters (BO,SO) of $\Delta u, D_{i;j;t}$. It is possible to consider the average delay constraint by using the specific queue size $B_{\max}$

3.Throughput

Here we characterize the GTS throughput, namely, the average amount of packets that can be transmitted during a GTS. Let Ps(t) be the probability that a GTS allocation is successful at the superframe *t*. Then

$$\begin{aligned}P_s(t) &= 1-P_{\text{drop}}(t)\\ &= 1-\frac{\mathbb{E}\left[r_d(t)\right]}{\sum_{k=1}^{L_{\max}}\lambda_k k\left(\sum_{i=0}^{B_{\max}}\pi_i^t+\pi_{B_{\max}^*}^t\right)}\ , \qquad .. (7)\end{aligned}$$

where Pdrop(t) is the drop probability due to the limited queue size Bmax at the superframe *t*. Note that Pdrop(t) is the ratio between the mean number of dropped requests, given by Eq. (18), and the mean number of total requests at the superframe *t*. As a number of requests increase, it increases the length of waiting queue and results on higher dropped probability. If we assume that the frame size DFS is smaller than Tcfp, then the normalized system throughput S(t) of the superframe *t* is given by the ratio of the average length of successfully allocated payload in a GTS time slot to the average length of a GTS time slot, namel where Lpl is the length of payload of

$$\mathrm{S}(t) = \frac{P_{\mathrm{S}}(t)\,L_{\mathrm{pl}}\,\tau_n}{\theta_{\min}\,T_{\mathrm{SS}}}\ , \qquad …. (6)$$

each data packet, T_n is the number of data packets, T_{SS} is the length of superframe slot, and μmin is the minimum number of superframe slots. The normalized system throughput S(t) depends on the traffic pattern since the drop probability $P_{\text{drop}}(t)$ is related to the number of data packets T_n, the frame size L_{fr}, the mean and variance of requests. Hence, the system throughput is related to the time effectively used for data transmission within a GTS. It is possible to derive the optimal protocol parameters (BO, SO) which maximize the throughput of GTS usage.

VI.NUMERICAL RESULTS

Here we present extensive Monte Carlo simulations of the GTS allocation to validate our theoretical results, which we then use for a performance analysis. The simulations are based on the specifications of the IEEE 802.15.4 [1], with beacon order set equal to superframe order, namely BO=SO. In the simulations, the number of GTS requests for each superframe follows some different probability density functions. In particular, the simulation experiments are obtained with Poisson, Normal, and Gamma distribution. We considered the Gamma distribution because many other distributions can be approximated by it. Furthermore, we investigated the effects of the protocol parameters (BO, SO) in terms of throughput and delay. Details follows in the sequel.

A. Validation

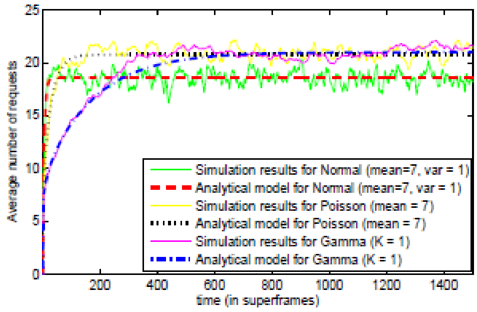
We validated the average number of requests, average delay of GTS allocation, the average number of dropped requests and the queue overflow probability as the time progress. Recall that the average number of dropped requests and the queue overflow probability are the important metrics for the stability of queue management.

Figs. 4(a), 4(b) compare the average number of waiting requests given by Eq. (3) and the average delay of requests given by Eq(6)with simulation results for different distributions of the number of GTS requests, respectively. The analytical model follows well the simulation results. By comparing Fig. 5(a) and Fig. 5(b), we confirm the strong dependence between the average number of requests and the average delay due to a FCFS fashion of the queue management. As a number of GTS requests increase during the CAP, the length of waiting queue and average delay increase.

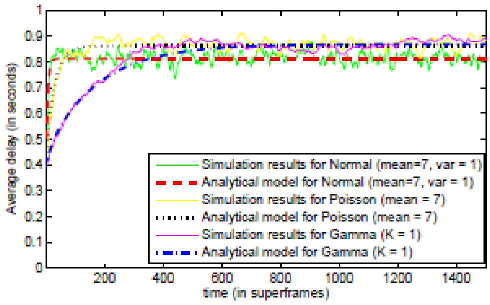
Figs. 5(a), 5(b) report the average number of dropped requests given by Eq. (4) and the overflow probability as obtained by Eq. (5) with simulations, respectively. Observe that our analytical model matches well the average overflow probability for every distribution of the number of GTS requests. Therefore, we conclude that we can apply the average number of dropped requests and the overflow probability to analyze the stability of the queue management, as we see next. In addition, since a number of GTS requests depend on the random access scheme of CAP, it will be interesting to investigate the impact of reliability in CAP to the stability issue of queue management of GTS allocation.

B. Effect of Beacon and Superframe Order

In this section, we investigate the impact of beacon order on the average throughput and delay when the Poisson distribution is assumed for the number of GTS requests. We remark here that similar behaviors as those investigated by using the Poisson distribution are observed by adopting the Normal and Gamma distributions.

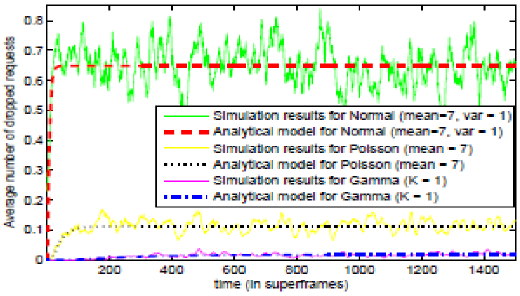


(a) Average number of requests



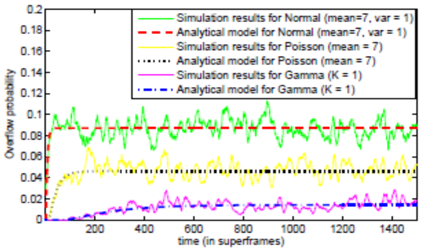
(b) Average delay of GTS allocation

Fig.4. Average number of waiting requests (a) and average delay of requests (b) as obtained by simulations and Eqs(3)&(6)



(a) Average number of dropped requests

Fig 5 (a)



(b) Queue overflow probability

Fig. 5. Stability of the queue management as obtained by simulations and analytical model of Eqs. (4) & (5).

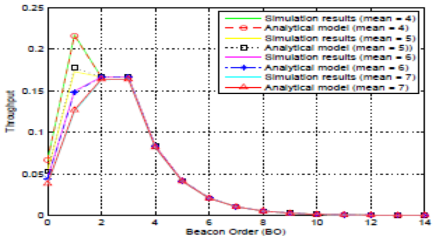
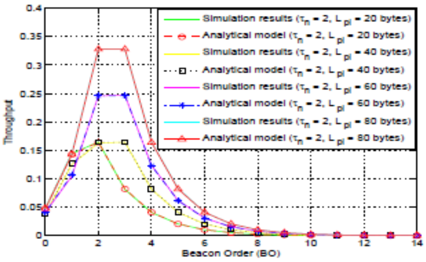
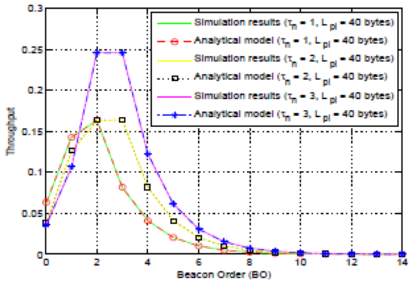


Fig. 6. Effect of beacon order on the throughput of GTS allocation as a function of the mean of the Poisson distribution



(a) Throughput as a function of L_{pl} (20, 40, 60, 80 bytes), the number of data packets $\tau_n = 2$.



(b) Throughput as a function of τ_n (1, 2, 3), the length of payload ($L_{\text{pl}} = 40$ bytes).

Fig. 7. Effect of the beacon order on the throughput of GTS allocation

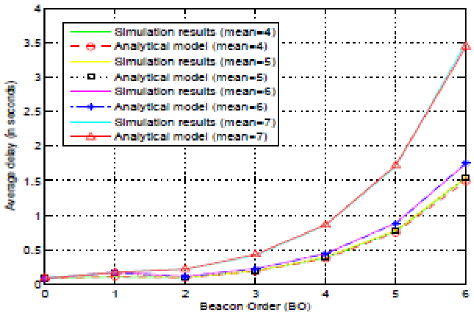


Fig. 8. Effect of beacon order on the average delay of GTS allocation

VII .CONCLUSIONS

In this paper, we presented an analytical model based on a Markov chain to compute the performance of the GTS allocation mechanism in IEEE 802.15.4 standard. Monte Carlo simulations validated the analysis. Our theoretical analysis gives accurate numerical results, which are different from the ones obtained in [10] by using the network calculus. We evaluated the stability of the queue size at the network coordinator, the delay to serve a GTS request, and the achieved throughput for different traffic patterns and protocol parameters. We derived the dependence of the average delay and queue size as a function of the number of requests. Furthermore, we analyzed the achieved throughput as a function of the amount of data packets to forward for each request. We observed that lower beacon order gives lower delay but ensures a worse throughput because of the higher drop probability. By contrast, higher beacon order increases significantly the average delay and degrades the throughput due to wasted bandwidth. Future work includes the model extension by considering the random access scheme of CAP.

REFERENCES

[1] *IEEE Std 802.15.4-2996, September, Part 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (WPANs)*, IEEE, 2006. [Online].Available: http://www.ieee802.org/15

[2] G. Lu, B. Krishnamachari, and C. Raghavendra, "Performance evaluation of the IEEE 802.15.4 MAC for low-rate low-power wireless networks," in *IEEE IPCCC*, Apr 2004.

[3] N. Timmons and W. Scanlon, "Analysis of the performance of IEEE 802.15.4 for medical sensor body area networking," in *IEEE SECON*, Oct 2004.

[4] L. Cheng, X. Zhang, and A. G. Bourgeois, "GTS allocation scheme revisited," *Electronics Letters*, 2007.

[5] J. K. Song, J. D. Ryoo, S. C. Kim, J. W. Kim, H. Y. Kim, and P. S. Mah, "A dynamic GTS allocation algorithm in IEEE 802.15.4 for QoS guaranteed real-time applications," in *IEEE ISCE*, 2007, pp. 1–6.

[6] S. E. Yoo, D. Y. Kim, M. L. Pham, Y. M. Doh, E. C. Choi, and J. D. Huh, "Scheduling support for guaranteed time services in IEEE 802.15.4 low rate WPAN," in *IEEE RTCSA*, 2005, pp. 400–406.

[7] C. Na, Y. Yang, and A. Mishra, "An optimal GTS scheduling algorithm for time-sensitive transactions in IEEE 802.15.4 networks," *Comput. Netw.*, pp. 2543–2557, 2008.

[8] Y. Huang, A. Pang, and H. Hung, "An adaptive GTS allocation scheme for IEEE 802.15.4," *IEEE Trans. Parallel Distrib. Syst.*, pp. 641–651, 2008.

[9] A. Koubaa and Y. Q. Song, "Evaluation and improvement of response time bounds for real-time applications under non-preemptive fixed priority scheduling," *International Journal of Production and Research (IJPR)*, pp. 2899–2913, July 2004.

[10] A. Koubaa, M. Alves, and E. Tovar, "GTS allocation analysis in IEEE 802.15.4 for real-time wireless sensor networks," in *IEEE IPDPS*, 2006, pp. 25–29.

[11] "Energy and delay trade-off of the GTS allocation mechanism in IEEE 802.15.4 for wireless sensor networks," *International Journal of Communication Systems*, 2006.

[12] "i-GAME: An implicit GTS allocation mechanism in IEEE 802.15.4 for time-sensitive wireless sensor networks," in *IEEE ECRTS*, 2006.