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Optimizing Performance of Slotted IEEE 802.15.4 Mac for Cap and GTS Allocation using Stochastic Petri Nets

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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. The IEEE 802.15.4 protocol proposes a flexible communication solution for Low-Rate Wireless Local Area Networks including sensor networks. It presents the advantage to fit different requirements of potential applications by adequately setting its parameters. When enabling its beacon mode, the protocol makes possible real-time guarantees by using its Guaranteed Time Slot (GTS) mechanism. In this work, the performance of both the modes of data transfer- the CAP and the GTS allocation mechanism in IEEE 802.15.4 is analyzed using stochastic model. The analysis gives a full understanding of the behavior of the CAP and GTS mechanism with regards to delay and throughput metrics. Accurate modeling of the delay constraints using GTS, considering acknowledgement signal by physical and network layer is provided. When addressing applications with soft or hard real 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. This work also provides the optimum energy consumptions as a function of duty cycle is evaluated using various system parameters considering the number of nodes in the system and the probability distribution of number of GTS requests. Analytical modeling is done using Stochastic Petri Nets (SPN) and simulation is carried out in MATLAB and results are compared with those analytically computed.

Key words: Wireless Sensor Networks, IEEE 802.11 MAC, Stochastic Modeling, Contention Period Protocols etc

I. INTRODUCTION

Given the benefits offered by wireless sensor networks (WSNs) compared to wired networks, such as, simple deployment, low installation cost, lack of cabling, and high mobility, WSNs present an appealing technology as a smart infrastructure for building and factory automation, and process control applications. Emerson Process Management [1] estimates that WSNs enable cost savings of up to 90% compared to the deployment cost of wired field devices. Several market forecasts have recently predicted exponential growths in the sensor network market over the next few years, resulting in a multi-billion dollar market in the near future. c. In particular, despite a challenging economy, ZigBee [2] annual unit sales have increased by 62% since 2007 and the market is on track to reach hundreds of millions of annual units within the next few years by over 350 global manufacturers. Similarly, ABI research [3] predicts that in 2015 around 645 million 802.15.4 chipsets will ship compared to 10 million in 2009. Although WSNs have a great potential for process, manufacturing and industrial applications, there is not yet a widespread use of WSNs. According to Gartner's Hype Cycles [4], WSNs are evolving very slowly into a mainstream adoption level. One of the fundamental reasons is that current technologies are not based on a design framework that is easy to use and applicable across several application domains. Today, each specific application development often requires expert knowledge over the stack: from the communication layer to application layer. This is evident for instance in the development of control systems based on WSNs. These systems are particularly challenging because they must support the right decision at the right moment despite any traffic condition, even in the presence of unexpected congestion, network failures or external manipulations of the environment. Furthermore, an energy efficient network operation is also a critical factor due to the limited battery lifetime of these sensors.

The IEEE 802.15.4 [2] standard is poised to become the global standard for low data rate, low energy consumption wireless sensor networks (WSN) for a wealth of application areas, such as environment monitoring, industrial process surveillance, home automation and personal health monitoring. Since its ratification, the IEEE 802.15.4 MAC has received much interest to assess its throughput and energy performance. In particular, the novel slotted access protocol featured in the contention access period (CAP) of its beacon-enabled mode has spurred much attention; many preliminary simulation studies [5,6] were conducted, and several accurate analytical models have been introduced.

Wireless sensor networking is one of the hot topics in computer science research. It is an emerging technology that have revolutionized the design of embedded systems and triggered a new set of potential applications including environment monitoring, smart spaces, medical systems and new domestic solutions. Such a network normally consists of a large number of distributed nodes that organize themselves in a multi-hop wireless network. Each node has one or more sensors, embedded processors and low-power radios, and is normally battery operated.

Typically, these nodes coordinate to perform a common task. The delivery of sensory data for process and analysis, usually to a control station (also referred as sink), is based on the collaborative routing work of the WSN nodes. Hence, a wireless sensor node should include some basic capabilities, namely sensing (eventually other I/O), processing (and memory) and wireless communications, acting namely as:

A. Data Source:

Producing sensory data by interacting with the physical environment and collecting a specified data needed for control (temperature, humidity, pressure, movement…).

B. Data Router:

Transmitting data from one neighbor sensor node to another, towards the control station, which processes and analyses the data collected from the different sensors/nodes in the network.

The IEEE 802.15.4 Task Group (TG4) and the ZigBee Alliance [2] have developed an entire communication protocol stack for Low-Rate Wireless Personal Area Networks (LR-WPAN). The IEEE 802.15.4 protocol specifies the Physical (PHY) Layer and Medium Access Control (MAC) sub-layer for LR-WPANs. The ZigBee protocol specifies the protocol layers above IEEE 802.15.4, specifically the Network Layer (NWK) and the Application Layer (APL), to provide a full protocol stack for low-cost, low-power, low data rate wireless communications.

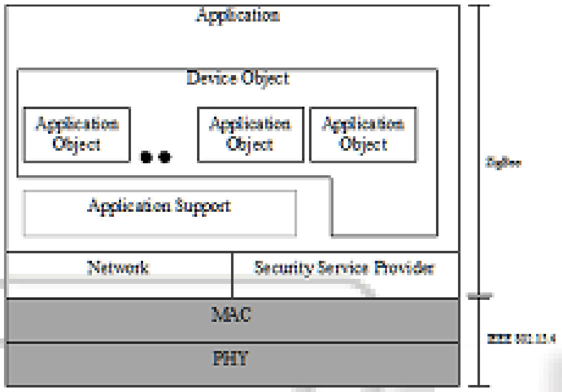

Fig 1.1: IEEE 802.15.4 and ZigBee Protocol Stack

One of the potential applications of these protocols is Wireless Sensor Networks (WSNs), which represent a new generation of distributed embedded systems for pervasive and ubiquitous computing [7]. Basically, the IEEE 802.15.4 MAC protocol can operate in the following two modes:

(1) Non beacon-enabled mode: In this mode, non-slotted CSMA/CA mechanism for medium access is generally used.
(2) Beacon-enabled mode: In this mode, beacons are periodically sent by a central device, called the Personal Area Network (PAN) Coordinator, or ZigBee Coordinator, to synchronize nodes that are associated with it, and to identify the PAN. The MAC protocol in this mode uses slotted CSMA/CA mechanism, but a Guaranteed Time Slot mechanism is also optionally available

C. Problem Statement:

Time-critical applications for wireless sensor networks [8] are an important class of services supported by the standard IEEE 802.15.4. Control, actuation, and monitoring are all examples of applications where information must be delivered within some deadline. Understanding the delay in the packet delivery is fundamental to assess performance and quality of service (QoS). In this work, the performance of IEEE 802.15.4 slotted MAC is analyzed for both contention access period (CAP) and contention free period (CFP) consisting of Guaranteed Time Slots (GTS) [9]. Moreover, the optimum energy consumption is also modelled as a function of various system parameters such as number of nodes and the frame length.

II. MOTIVATION AND RESEARCH APPROACH

Many MAC and routing protocols are developed for WSNs. However, most recent products of WSNs use standard-based networking and RF solutions. The recent release of standards from IEEE, Internet Engineering Task Force (IETF), and International Society of Automation (ISA) [10], brought the technology out of research labs and developed the numerous commercial products. The standard specifies the physical layer and the MAC sub layer for low-rate wireless networks. The star network is a basic network topology, where all N nodes contend to send data to the PAN coordinator, which is the data sink. The standard defines two channel access modalities: the beacon-enabled modality, which uses a slotted CSMA/CA and the optional guaranteed time slot (GTS) allocation mechanism, and a simpler unslotted CSMA/CA without beacons. The communication is organized in temporal windows denoted superframes. The IEEE 802.15.4 MAC protocol can support energy efficient, reliable and timely packet transmission by tuning the medium access control parameters macMinBE, macMaxCSMABackoffs, and macMaxFrameRetries. Such a tuning is difficult, because simple and accurate models of the influence of these parameters on the probability of successful packet transmission, packet delay, and energy consumption are not available. Moreover, it is not clear how to adapt the parameters to the changes of the network and traffic regimes by algorithms that can run on resource-constrained nodes. In this dissertation, a generalized stochastic Petri Net (GSPN) [11] is proposed to model these relations by simple expressions without giving up the accuracy.

A Stochastic Petri Net (SPN) [11] model is presented to model the stability, delay, and throughput of GTS allocation. A tradeoff is also derived between energy consumption and real time packet transfer and non real time packet transfer. In the beacon-enabled mode of IEEE 802.15.4 Medium Access Control (MAC), a Wireless Personal Area Networks (WPAN) coordinator broadcasts beacons to the devices at regular superframe intervals to maintain synchronization of the devices. A superframe interval comprises the active and inactive duration, and the active part consists of contention access period (CAP) and contention free period (CFP). Devices exchange time-sensitive data streams in CFP, while devices contend for transmission of asynchronous data in CAP. IEEE 802.15.4 employs specially designed slotted CSMA/CA based MAC during CAP of a superframe to save power consumption, which is an essential requirement for battery powered small or portable WPAN devices. The rationale of the slotted CSMA/CA mechanism is to minimize the power consuming intervals for channel sensing and backoff. Recently, there have been simulation-based studies focusing on performance of beacon-enabled MAC, and on feasibility of low-rate WPAN with several application scenarios, and analysis study on beacon-enabled WPAN [12]. Although typical traffic load and duty cycle is small in low rate-WPANs, we may not preclude the possibility of future large-scale deployment of WPANs. In addition, there is a clear distinction between CSMA/CA of IEEE 802.15.4 and that of the others. In this sense, it is vital to present a new model with the theoretical limit. In this letter, a new analytical model for slotted CSMA/CA of IEEE 802.15.4 MAC is presented, and its performance limit is studied. Simulations are presented which shows a closed match with analytical results.

III. PERFORMANCE MODELING OF SLOTTED IEEE 802.15.4 MAC FOR CAP AND GTS ALLOCATION USING STOCHASTIC PETRI NETS

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 Δ_u in a superframe is considered according to the IEEE 802.15.4 specifications. The number of requests of GTSs depends on the number of time critical data packets that the devices want to send to the PANC. With contention-based transmissions during CAP, there will be loss of GTS requests due to data collisions in CAP. Hence, the performance of the GTS allocation mechanism in CFP is dependent on the number of requests that arrive successfully to the PANC during the CAP. Such a number is modelled by using a probability distribution, which abstracts the contention-based transmissions during CAP and possible collisions.

Let n(t) be a non-negative integer representing the number of waiting requests at the beginning of the current superframe t. Then n(t) ϵ {0,.....,B_{MAX}}. However, the number of requests arrived at the PAN coordinator may be more than B_{MAX} but these requests are dropped as the maximum capacity of the queue is B_{MAX} and the queue discipline being FCFS. It is assumed that there is no reallocation of GTS.

Also $B_{MAX} = \Delta_u*(N_{GPT} +1)$ where Δ_u is the maximum number of GTS time slots for each superframe and N_{GPT} = aGTSDescPersistenceTime. After NGPT superframes later, the GTS description of the beacon is removed. When there are k requests, $\Delta_u < k <$ Bmax, then some requests k - Δ_u will be delayed to obtain GTS in the next superframe. Consider N nodes connected to PAN coordinator in star topology. It is assumed that each user transmits with probability p within a time period T_F, where T_F denotes the time slot length of the slotted CSMA. The average number of frames sent to the coordinator within a period of time T_F is simply λ=N*p.

The results for various values of the T_{CAP} , λ, Δ_u and B_{MAX} is derived in the next chapter.

The arrival of these frames in the system is independent of each other with a rate of λ, which is the average number of packet transmissions during a time T_F. This rate is modelled by the Poisson Distribution

$$P(k) = P_k = \frac{\lambda^k e^{-\lambda}}{k!}$$

Where P(k) is the probability that k packet transmissions occurs within time T_F. The term vulnerable period is used to denote the period of time in which a packet can possibly collide with a given packet x. In case of slotted CSMA, this vulnerable period is equal to the length of the time slot as every node can start transmitting a packet only at the start of a time slot. This means that two packets can either collide completely or do not overlap at all. The probability of successful packet transmission can be obtained as follows:

P{packet x successfully delivered}
=P{no packets transmitted within vulnerable period T}
=P(0)
=$e^{-\lambda}$
=e^{-Np}

Thus, throughput of the system is:
T = N*p* e^{-Np}

It gives the average rate of successful message delivery over the channel. Throughput, in this case, takes the maximum value of 18% (=1/e) at N*p=1.

Let P_{GTS} denotes the (independent) probability that a packet transmission corresponds to a GTS request. This is a critical assumption and the value of P_{GTS} is different for different nodes of the network. In this work, the value of P_{GTS} is assumed to be a constant and same for all the nodes of the network. However, results are shown for various values of P_{GTS} under various values of the system parameters.

Thus, the average number of GTS requests sent to the PAN coordinator is:

$$N'_{GTS} = P_{GTS}* N*p* e^{-Np}$$

Let T_{CAP} denotes the Contention Access Period, measured in time slots. Therefore, the average number of GTS requests sent during the CAP is $N_{GTS} = T_{CAP}* N*p* e^{-Np}$

Thus, this is the average number (rate) of waiting requests for GTS allocation at the beginning of a next superframe structure.

Modelling this rate as the Poisson Probability Distribution, one can write

$$P(N_{GTS} = k) = P_k = \frac{\left(T_{CAP} * \mathrm{N} * \mathrm{p} * \ e^{-(\mathrm{N}*\mathrm{p})}\right)^{\mathrm{k}} e^{-(\lambda * T_{CAP})}}{k!}$$

The expected number of GTS requests sent to the PAN coordinator in T_{CAP} is

$$EX \ = \sum_{k=1}^{N} k * P_k$$

The solution of equation 3.2 follows the form

$$\mathrm{EX} = 1 * P_1 + 2 * P_2 + 3 * P_3 + \cdots \infty$$

The value for the same is derived in the next chapter.

A. *MAC Functions of Slotted CSMA/CD:*

In slotted CSMA/CA of IEEE 802.15.4, three counters are maintained in each device for channel access control. NB is the number of backoff trials (backoff stage) for the transmission of a frame. BE is the backoff exponent to generate a random backoff duration for which a device has to wait before attempting carrier sensing. CW is the value of the contention window slots for clear channel assessment (CCA) after the random backoff duration.

Let k denote the backoff stage NB of a device. And, let $w_k = 2^{\mathrm{BEk}}$ be the backoff window at backoff stage k of a device, where backoff exponent BE_k = 3, 4, 5, 5, and 5 for $0 \leq k \leq m$ (m = 4). Initially (k = 0), a device with a pending frame for transmission selects a random backoff counter value among $[0, w_0-1]$ slots and the backoff counter value decrements automatically at every slot until it becomes zero regardless of channel status, i.e., without performing CCA. In this way, the device can save power consumption for medium sensing, which is clearly different from the conventional CSMA/CA mechanism in IEEE 802.11 Wireless Local Area Networks (WLAN)? Next, before attempting access to the wireless medium, the device performs carrier sensing (CCA) during two contention window slots. The CW starts from two and decreases by one at every idle contention window slot until it becomes zero. If either of two contention window slots is sensed busy, it immediately increases back off stage k and resets CW to two. Then, it repeats the backoff count-down procedure with a new random back off counter value among $[0, w_k - 1]$, and carrier sensing (up to two contention window slots) until the back off stage $k = m$. If neither of two contention window slots for CCA is sensed busy at any back off stage k, the device can have a chance to transmit the frame. The transmitted frame can be considered as either success or failure (collision) depending on whether the ACK frame is successfully received or not within a specified time interval. In addition, if the channel is continuously sensed busy for five consecutive carrier sensing, the transmission also fails. Note that one carrier sensing corresponds to up to two contention window (CCA) slots after a random back off duration. When the device fails transmission either due to five consecutive busy channels or due to a collision, the device is allowed to retransmit the frame up to three times. In that case, the retransmission phase starts with a random back off counter value among $[0, w_k - 1]$ with back off stage $k = 0$. After three retransmission failures, the frame is dropped eventually.

B. GSPN (Generalized Stochastic Petri Net) Model for CAP of IEEE 802.15.4:

Figure 3.1 denotes the GSPN model for any node in the sensor network working in conjunction with the PAN coordinator. The description of the proposed GSPN model is as follows:

A token at a place P0 denotes that the node has no data to send. Transition T0 moves the token to the place P1 which denotes that the node has a data packet to send. This transition rate is proportional to the probability with which each packet sends the data to the PAN coordinator. Transition T1 moves the packet from place P1 to P3 which denotes the successful packet transmission after CCA. Immediate transition from P3 to P0 moves the token from P3 back to P0. Transition T1 is proportional to the probability of successful packet delivery in the slotted CSMA. Transition T2 moves the token from place P1 to P4 and this transition rate is proportional to the probability of busy carrier, thereby moving to a period of random backoff. Token at the place P4 indicates a carrier sensing of busy period and it is followed by an immediate transition to the place P5. Token at a place P5 will wait for a random backoff time before sensing the medium again. Transition T5 moves the token from place P5 back to P1. In this simulation, the transition rate T5 is proportional to the average time the backoff period taken when considering random backoffs.

Transition T3 moves the token from place P0 to place P2 which indicates a request for GTS allocation. The place P2 is followed through transitions T7 and T8 to places P6 and P7 respectively. Transition T7 moves the token to the place P6 which indicates a successful GTS allocation whereas transaction T8 moves the token to the place P7 which indicates the failure of GTS allocation and is followed by immediate transition T9 to the place P2. The place P6 is a state in which the node gets confirmation of GTS allocation. It is assumed that successful delivery occur thereof and thus, followed by immediate transition T10 to the place P0.

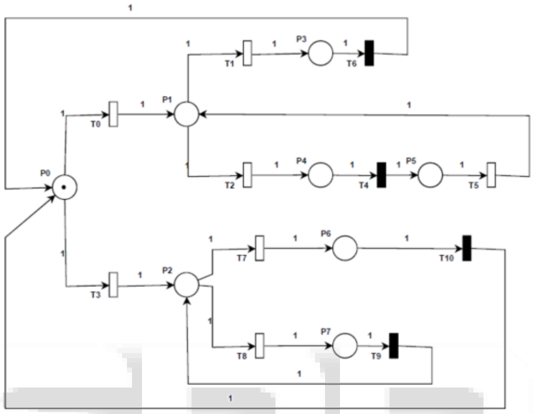

Fig. 3.1: SPN model for any node requiring data transmission in CAP or requiring a GTS slot, on a probabilistic analysis

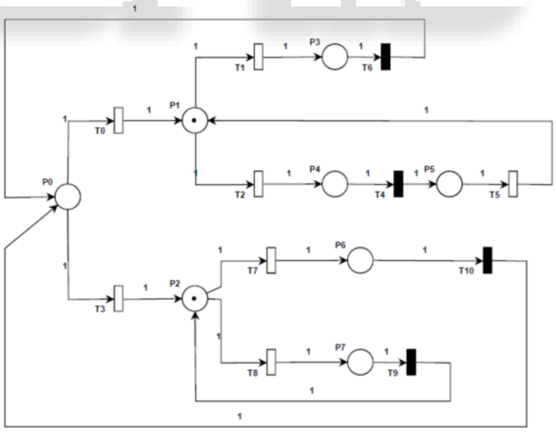

Fig 3.2: SPN model for CAP and GTS allocation simultaneously

The complete GSPN analysis of the model and the corresponding solutions are provided in chapter 4. The analysis give a complete description in terms of sojourn times, the mean waiting time before the successful transmission at any state of the model. This gives an accurate measure of the Quality of Service in terms of delay in packet transmission.

IV. ANALYSIS OF PROPOSED WORK

The analysis of the proposed SPN model for LRWPAN is investigated in this chapter. The two SPN models described in chapter 3 proposes two different ways of packet transmission. The first SPN model (Fig 3.1) describes the logic (to be specified in the application layer) that a node has data packet to send to the PAN coordinator. This data packet can be sent in the CAP of the superframe or the node can request a GTS for guaranteed delay. This decision can be taken on the basis of some priority depending upon the criticality of the packet to be transferred, or the importance of the packet transfer in some context.

The second SPN model (Fig 3.2) describes the scenario when the node having a data packet for transmission, tries to send the packet in the CAP of the superframe and also request for a GTS slot. This type of programming of the zigbee radios is common for hard real time requirements as considered in sensing radiations in nuclear power plants.

Results obtained are then analyzed with those that are obtained using Network Calculus as described in [ref].

A. Parameter Specification for Proposed SPN:

Consider the following parameter specification modeling a generic Wireless Sensor Network. The specifications presented below are applicable for a wide range of physical situations including fire alarm installations in critical regions of a building, nuclear power plants or health care systems.

Transition	**Specification**	**Transition Rate Values**
T_0	Transition indicating Data Transmission in CAP of superframe structure.	1
T_1	Transition indicating successful packet transmission after CCA.	0.36*
T_2	Transition indicating a busy carrier.	0.64
T_3	Transition indication a request for GTS allocation	0.1
T_4	Immediate Transition indicating a random backoff time	--
T_5	Transition to the state of carrier sensing for data transmission	0.64
T_6	Immediate transition after successful packet transmission	--
T_7	Transition indicating successful GTS allocation	0.36*
T_8	Transition indicating unsuccessful GTS allocation	0.64
T_9	Immediate Transition again to the GTS request state	--
T_{10}	Immediate Transition indicating successful GTS allocation	--

Table 4.1: Specifications of Parameters For Deducing Results

*Throughput of slotted aloha

B. Derivation of Expected number of GTS requests to the PAN coordinator:

The arrival rate for number of requests for GTS allocation depends on the specifc type of the Wireless Sensor Network under consideration. In this work, Poisson Probability Distribution is considered. The probability distribution of the random variable, under varying rates of incoming GTS requests can be modeled as given below

Rate	**1**	**2**	**3**	**4**	**5**
Number of GTS requests					
1	3.679 E-01	2.707 E-01	1.494 E-01	7.326 E-02	3.369 E-02
2	1.839 E-01	2.707 E-01	2.240 E-01	1.465 E-01	8.422 E-02
3	6.131 E-02	1.804 E-01	2.240 E-01	1.954 E-01	1.404 E-01
4	1.533 E-02	9.022 E-02	1.680 E-01	1.954 E-01	1.755 E-01
5	3.066 E-03	3.609 E-02	1.008 E-01	1.563 E-01	1.755 E-01
6	5.109 E-04	1.203 E-02	5.041 E-02	1.042 E-01	1.462 E-01
7	7.299 E-05	3.437 E-03	2.160 E-02	5.954 E-02	1.044 E-01
8	9.124 E-06	8.593 E-04	8.102 E-03	2.977 E-02	6.528 E-02
9	1.014 E-06	1.909 E-04	2.701 E-03	1.323 E-02	3.627 E-02
10	1.014 E-07	3.819 E-05	8.102 E-04	5.292 E-03	1.813 E-02
11	9.216 E-09	6.944 E-06	2.210 E-04	1.925 E-03	8.242 E-03
12	7.680 E-10	1.157 E-06	5.524 E-05	6.415 E-04	3.434 E-03
13	5.908 E-11	1.780 E-07	1.275 E-05	1.974 E-04	1.321 E-03
14	4.220 E-12	2.543 E-08	2.732 E-06	5.640 E-05	4.717 E-04
15	2.813 E-13	3.391 E-09	5.463 E-07	1.504 E-05	1.572 E-04
16	1.758 E-14	4.239 E-10	1.024 E-07	3.760 E-06	4.914 E-05
17	1.034 E-15	4.987 E-11	1.808 E-08	8.847 E-07	1.445 E-05
18	5.746 E-17	5.541 E-12	3.013 E-09	1.966 E-07	4.015 E-06
19	3.024 E-18	5.833 E-13	4.757 E-10	4.139 E-08	1.056 E-06
20	1.512 E-19	5.833 E-14	7.135 E-11	8.277 E-09	2.641 E-07

Table 4.2: Probability Distribution of Number of GTS Requests for Various Values Of Arrival Rates

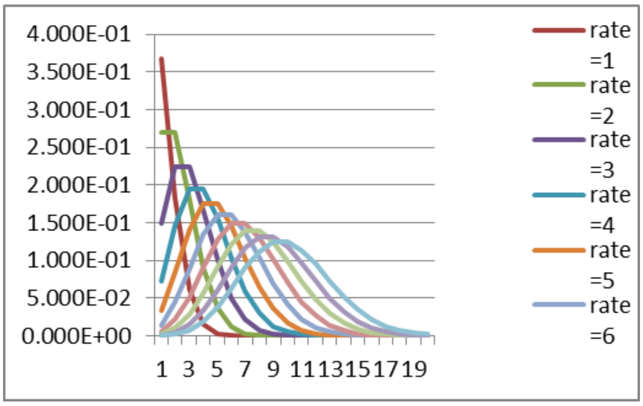

Fig 4.1: Plot of Table 4.1

Let N be the number of nodes and let p be the probability of transmission of a data packet or GTS requests by any node in a successive time slot. Therefore, the number of data frames or GTS requests waiting to be processed in the subsequent time slot are N*p. The probability of successful packet delivery is e^{-N*p} , thus the throughput, of the network is $T = N*p* e^{-Np}$

Rate	1	2	3	4	5	6
Number of GTS requests						
1	3.679E-01	2.707E-01	1.494E-01	7.326E-02	3.369E-02	1.487E-02
2	1.839E-01	2.707E-01	2.240E-01	1.465E-01	8.422E-02	4.462E-02
3	6.131E-02	1.804E-01	2.240E-01	1.954E-01	1.404E-01	8.924E-02
4	1.533E-02	9.022E-02	1.680E-01	1.954E-01	1.755E-01	1.339E-01
5	3.066E-03	3.609E-02	1.008E-01	1.563E-01	1.755E-01	1.606E-01
6	5.109E-04	1.203E-02	5.041E-02	1.042E-01	1.462E-01	1.606E-01
7	7.299E-05	3.437E-03	2.160E-02	5.954E-02	1.044E-01	1.377E-01
8	9.124E-06	8.593E-04	8.102E-03	2.977E-02	6.528E-02	1.033E-01
9	1.014E-06	1.909E-04	2.701E-03	1.323E-02	3.627E-02	6.884E-02
10	1.014E-07	3.819E-05	8.102E-04	5.292E-03	1.813E-02	4.130E-02
11	9.216E-09	6.944E-06	2.210E-04	1.925E-03	8.242E-03	2.253E-02
12	7.680E-10	1.157E-06	5.524E-05	6.415E-04	3.434E-03	1.126E-02
13	5.908E-11	1.780E-07	1.275E-05	1.974E-04	1.321E-03	5.199E-03
14	4.220E-12	2.543E-08	2.732E-06	5.640E-05	4.717E-04	2.228E-03
15	2.813E-13	3.391E-09	5.463E-07	1.504E-05	1.572E-04	8.913E-04
16	1.758E-14	4.239E-10	1.024E-07	3.760E-06	4.914E-05	3.342E-04
17	1.034E-15	4.987E-11	1.808E-08	8.847E-07	1.445E-05	1.180E-04
18	5.746E-17	5.541E-12	3.013E-09	1.966E-07	4.015E-06	3.932E-05
19	3.024E-18	5.833E-13	4.757E-10	4.139E-08	1.056E-06	1.242E-05
20	1.512E-19	5.833E-14	7.135E-11	8.277E-09	2.641E-07	3.725E-06

Table 4.2: Throughput Analysis of Packet Transmission

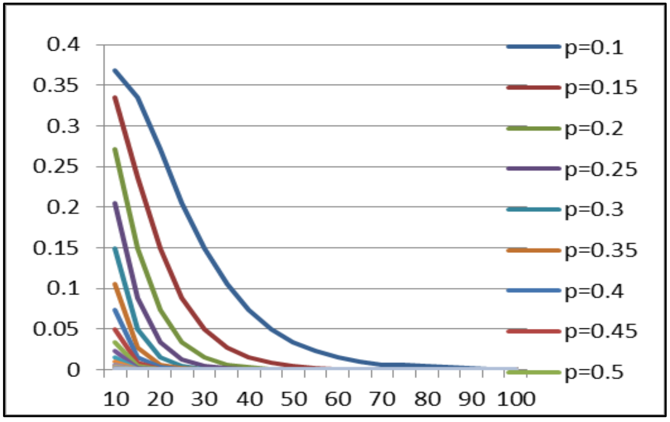

Fig. 4.2: Plot of table 4.2 for throughput analysis of Packet Transmission

C. GSPN Analysis for SPN model for any node requiring data transmission in CAP or requiring a GTS slot, on a probabilistic analysis:

The analysis of the stochastic model prepared through petri net can be done using PIPE simulation. The complete simulation results for PIPE simulation are as follows:

1) Classification results:

Network Equivalent	Value
State Machine	True
Marked Graph	False
Free Choice Net	True
Extended Free Choice Net	True
Simple Net	True
Extended Simple Net	True

GSPN Steady State Analysis Results: Tangible and Vanishing States

Set of Tangible States:

	P0	P1	P2	P3	P4	P5	P6	P7
M0	1	0	0	0	0	0	0	0
M1	0	0	1	0	0	0	0	0
M2	0	1	0	0	0	0	0	0
M3	0	0	0	0	0	1	0	0

Steady State Distribution of Tangible States

Marking	Value
M0	0.25
M1	0.25
M2	0.25
M3	0.25

Average Number of Tokens on a Place

Place	Number of Tokens
P0	0.25
P1	0.25
P2	0.25
P3	0
P4	0
P5	0.25
P6	0
P7	0

Token Probability Density

	"μ" = 0	"μ" = 1
P0	0.75	0.25
P1	0.75	0.25
P2	0.75	0.25
P3	1	0
P4	1	0
P5	0.75	0.25
P6	1	0
P7	1	0

Throughput of Timed Transitions

Transition	Throughput
T0	0.25
T1	0.25
T2	0.25
T3	0.25
T4	0.25
T5	0.25
T6	0.25
T7	0.25
T8	0.25

Sojourn times for tangible states

Marking	Value
M0	0.5
M1	0.5
M2	0.5
M3	1

State space exploration took 1.061s
Solving the steady state distribution took 0.265s
Total time was 1.763s
Petri net invariant analysis results
T-Invariants

T0	T1	T2	T3	T4	T5	T6	T7	T8	T9
0	0	1	1	0	0	0	1	0	0
0	0	0	0	1	1	0	0	0	0
1	1	0	0	0	0	1	0	0	0
0	0	0	0	0	0	0	0	1	1

The net is covered by positive T-Invariants; therefore it might be bounded and live.

P-Invariants

P0	P1	P2	P3	P4	P5	P6	P7
1	1	1	1	1	1	1	1

The net is covered by positive P-Invariants, therefore it is bounded.
P-Invariant equations
M(P0) + M(P1) + M(P2) + M(P3) + M(P4) + M(P5) + M(P6) + M(P7) = 1
Analysis time: 0.016s
Petri net incidence and marking
Forwards incidence matrix I+

	T0	T1	T2	T3	T4	T5	T6	T7	T8	T9
P0	0	0	1	0	0	0	0	1	0	0
P1	1	0	0	0	0	0	1	0	0	0
P2	0	0	0	0	1	0	0	0	0	0
P3	0	1	0	0	0	0	0	0	0	0
P4	0	0	0	1	0	0	0	0	0	0
P5	0	0	0	0	0	1	0	0	0	0
P6	0	0	0	0	0	0	0	0	1	0
P7	0	0	0	0	0	0	0	0	0	1

Backwards incidence matrix I+

	T0	T1	T2	T3	T4	T5	T6	T7	T8	T9
P0	1	0	0	0	1	0	0	0	0	0
P1	0	1	0	1	0	0	0	0	0	0
P2	0	0	0	0	0	0	0	0	1	1
P3	0	0	0	0	0	0	0	1	0	0
P4	0	0	0	0	0	1	0	0	0	0
P5	0	0	0	0	0	0	1	0	0	0
P6	0	0	1	0	0	0	0	0	0	0
P7	0	0	0	0	0	0	0	0	0	0

Combined incidence matrix I

	T0	T1	T2	T3	T4	T5	T6	T7	T8	T9
P0	-1	0	1	0	-1	0	0	1	0	0
P1	1	-1	0	-1	0	0	1	0	0	0
P2	0	0	0	0	1	0	0	0	-1	-1
P3	0	1	0	0	0	0	0	-1	0	0
P4	0	0	0	1	0	-1	0	0	0	0
P5	0	0	0	0	0	1	-1	0	0	0
P6	0	0	-1	0	0	0	0	0	1	0
P7	-1	0	1	0	-1	0	0	1	0	0

Inhibition matrix H

	T0	T1	T2	T3	T4	T5	T6	T7	T8	T9
P0	0	0	0	0	0	0	0	0	0	0
P1	0	0	0	0	0	0	0	0	0	0
P2	0	0	0	0	0	0	0	0	0	0
P3	0	0	0	0	0	0	0	0	0	0
P4	0	0	0	0	0	0	0	0	0	0
P5	0	0	0	0	0	0	0	0	0	0
P6	0	0	0	0	0	0	0	0	0	0
P7	0	0	0	0	0	0	0	0	0	0

Enabled transitions

T0	T1	T2	T3	T4	T5	T6	T7	T8	T9
Yes	No	No	Yes	No	No	No	No	Yes	No

Minimal Siphons
{ P0, P1, P2, P3, P4, P5, P6, P7 }
Minimal Traps

{ P0, P1, P2, P3, P4, P5, P6, P7 }
Analysis time
0.016s
Reachability Graph

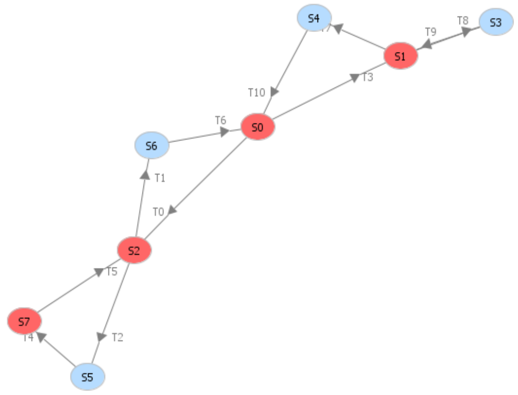

Fig. 4.3: Reachability Graph for SPN model described in Chapter 3

Petri net simulation results

Place	**Average number of tokens**	**95% confidence interval (+/-)**
P0	0.18812	0.04493
P1	0.14851	0.06185
P2	0.22772	0.07704
P3	0.07921	0.03682
P4	0.06931	0.03958
P5	0.06931	0.03958
P6	0.09901	0.04526
P7	0.11881	0.06943

Petri net state space analysis results

Bounded	True
Safe	True
Deadlock	False

Steady State Analysis Results

Set of Tangible States

	P0	P1	P2	P3	P4	P5	P6	P7
M0	1	0	0	0	0	0	0	0
M1	0	0	1	0	0	0	0	0
M2	0	1	0	0	0	0	0	0
M3	0	0	0	0	0	1	0	0

Steady State Distribution of Tangible States

Marking	Value
M1	0.25
M2	0.25
M3	0.25
M4	0.25

The above results indicate that optimal performance can be achieved under steady state arrival of data packets for CSMA protocol. Under heavy loads, the CAP period is to be increased so as to allow the packets to send the data packets over a long interval of time. The CFP consists of only 7 GTS, so CAP can be increased by reducing the sleep interval thereby reducing the sleep time, and consequently more power dissipation. Under Light load, the sleep interval can be increased as there are few collisions in the CAP and thus the battery life can be increased.

V. CONCLUSION AND FUTURE SCOPE

The main features of IEEE 802.15.4 standard are network flexibility, low cost, very low power consumption, and low data rate in an Adhoc self-organizing network among inexpensive fixed, portable and moving devices. It is developed for applications with relaxed throughput requirements which cannot handle the power consumption of heavy protocol stacks. 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. In this dissertation, the behavior 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. Moreover, in this dissertation, a novel stochastic characterization of the delay and packet loss probability distribution, and energy consumption for a unclustered network topology with slotted IEEE 802.15.4 has been made. The analysis was based on the stochastic modeling using Stochastic Petri Nets modeling data packet transmission. The analysis can be used efficiently to provide a set of optimal sleep and listening times that minimize the energy consumption of the network while guaranteeing latency and reliability constraints. Compared to existing protocols that minimize only the energy consumption, our optimization is based on probability distribution and gives much better results. Thus our method can be effectively employed to ensure a longer lifetime of the network.

REFERENCES

[1] Bonivento, L. Carloni, and A. Sangiovanni-Vincentelli, "Platform-based design for wireless sensor networks," Mobile Netw. Appl., 2008.

[2] IEEE 802.15.4, Part 15.4, Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (WPANs) (IEEE standard for information technology, 2006)

[3] ABI research. Wireless Sensor Networking Markets, 2010. http://www.abiresearch.com/research/1003936

[4] Gartner. Gartner's Hype Cycle Special Report, 2010. http://www.gartner.com/technology/research/hype-cycles/index.jsp

[5] J. Zheng and M. J. Lee, "Will IEEE 802.15.4 make ubiquitous net-working reality? - a discussion on a potential low power, low bit rate standard," IEEE Comm. Mag., vol.42, pp.140–146,Jun.2004.

[6] A. oubaa, M. Alves, and E. Tovar, "A comprehensive simulation study of slotted CSMA/CA for IEEE 802.15.4 wireless sensor networks," in IEEE Proc. of Work. on Factory Comm. Sys. ,Jun.2006,pp.183–192

[7] Munir, S.A.; Biao Ren; Weiwei Jiao; Bin Wang; Dongliang Xie; Jian Ma, "Mobile Wireless Sensor Network: Architecture and Enabling Technologies for Ubiquitous Computing," Advanced Information

Networking and Applications Workshops, 2007, AINAW '07. 21st International Conference on , vol.2, no., pp.113,120, 21-23 May 2007 doi: 10.1109/AINAW.2007.257

[8] Zheng, Tao; Gidlund, Mikael; Akerberg, Johan, "Deterministic medium access mechanism for time-critical wireless sensor network applications," Personal Indoor and Mobile Radio Communications (PIMRC), 2013 IEEE 24th International Symposium on , vol., no., pp.1598,1602, 8-11 Sept. 2013 doi: 10.1109/PIMRC.2013.6666397

[9] Huasong Cao; González-Valenzuela, S.; Leung, V.C.M., "Employing IEEE 802.15.4 for Quality of Service Provisioning in Wireless Body Area Sensor Networks," Advanced Information Networking and Applications (AINA), 2010 24th IEEE International Conference on , vol., no., pp.902,909, 20-23 April 2010 doi: 10.1109/AINA.2010.58

[10] Munro, J.K., "Application of security metrics to instrument systems that use distributed processing," Future of Instrumentation International Workshop (FIIW), 2011, vol., no., pp.5,8, 7-8 Nov. 2011 doi: 10.1109/FIIW.2011.6476809.

[11] Rongfei Zeng; Chuang Lin; Yixin Jiang; Xiaowen Chu; Fangqin Liu, "Performance Analysis of Data Management in Sensor Data Storage via Stochastic Petri Nets," Global Telecommunications Conference (GLOBECOM 2010), 2010 IEEE , vol., no., pp.1,5, 6-10 Dec. 2010 doi: 10.1109/GLOCOM.2010.5683539.

[12] Kasireddy, A.R.; Roy, D.A.; Ganti, R.K., "Energy efficient outsider attacks on IEEE 802.15.4 beacon enabled wireless sensor networks," Communications (NCC), 2014 Twentieth National Conference on , vol., no., pp.1,6, Feb. 28 2014-March 2 2014 doi: 10.1109/NCC.2014.6811301.

[13] Nanda, S.; Balachandran, K.; Kumar, S., "Adaptation techniques in wireless packet data services," Communications Magazine, IEEE , vol.38, no.1, pp.54,64, Jan 2000 doi: 10.1109/35.815453

[14] Shuo Xiao; Xueye Wei; Yu Wang, "Energy-efficient schedule for object detection in Wireless Sensor Networks," Service Operations and Logistics, and Informatics, 2008. IEEE/SOLI 2008. IEEE International Conference on , vol.1, no., pp.602,605, 12-15 Oct. 2008 doi: 10.1109/SOLI.2008.4686468

[15] Jardosh, S.; Ranjan, P., "Topology control algorithm for IEEE 802.15.4 based single sink wireless sensor networks," Advanced Networks and Telecommunication Systems (ANTS), 2011 IEEE 5th International Conference on , vol., no., pp.1,6, 18-21 Dec. 2011. doi: 10.1109/ANTS.2011.6163647

[16] IEEE Standard for Information Technology-Telecommunications and Information Exchange Between Systems-Local and Metropolitan Area Networks-Specific Requirements-Part 17: Resilient Packet Ring (RPR) Access Method and Physical Layer Specifications," IEEE Std 802.17-2004 , vol., no., pp.0_1,664, 2004 doi: 10.1109/IEEESTD.2004.94804

[17] Meghji, M.; Habibi, D.; Ahmad, I., "Performance evaluation of 802.15.4 Medium Access Control during network association and synchronization for sensor networks," Ubiquitous and Future Networks (ICUFN), 2012 Fourth International Conference on , vol., no., pp.27,33, 4-6 July 2012 doi: 10.1109/ICUFN.2012.6261659

[18] Chunyuan Li; Lifang Zhai; Liping Sun, "WMOS: A Wireless Message-Oriented System for Wireless Sensor Networks," Information Engineering (ICIE), 2010 WASE International Conference on , vol.1, no., pp.300,303, 14-15 Aug. 2010 doi: 10.1109/ICIE.2010.78

[19] Deng Zhixiang; Qi Bensheng, "Three-layered routing protocol for WSN based on LEACH algorithm," Wireless, Mobile and Sensor Networks, 2007. (CCWMSN07). IET Conference on , vol., no., pp.72,75, 12-14 Dec. 2007

[20] Ozen, S.; Oktug, S., "Forwarder set based dynamic duty cycling in asynchronous wireless sensor networks," Wireless Communications and Networking Conference (WCNC), 2014 IEEE , vol., no., pp.2432,2437, 6-9 April 2014.