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GTS Allocation Of IEEE 802.15.4 Used in Irrigation System

KEYWORDS: Drip Irrigation, Low-Rate Wireless Personal Area Networks (LR-WPAN), CSMA/CA, IEEE 802.15.4 parameters, Contention-Free Period (CFP),Contention Access Period (CAP), Beacon Interval (BI), Superframe Order (SO),

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ABSTRACT *The accurate determination of an irrigation schedule is a time-consuming and complicated process. The introduction of computer programs, however, has made it easier and it is possible to schedule the irrigation water supply exactly according to the water needs of the crops. Ideally, at the beginning of the growing season, the amount of water given per irrigation application, also called the irrigation depth, is small and given frequently. This is due to the low evapotranspiration of the young plants and their shallow root depth. During the mid season, the irrigation depth should be larger and given less frequently due to high evapotranspiration and maximum root depth. Thus, ideally, the irrigation depth and/or the irrigation interval (or frequency) vary with the crop development. When sprinkler and drip irrigation methods are used, it may be possible and practical to vary both the irrigation depth and interval during the growing season. With these methods it is just a matter of turning on the tap longer/shorter or less/more frequently. When surface irrigation methods are used, however, it is not very practical to vary the irrigation depth and frequency too much. With, in particular, surface irrigation, variations in irrigation depth are only possible within limits. It is also very confusing for the farmers to change the schedule all the time. Therefore, it is often sufficient to estimate or roughly calculate the irrigation schedule and to fix the most suitable depth and interval. Irrigation water supply is implemented by wireless sensor network.for guarnted time slot between water supply as per demand of crops we use IEEE 802.15.4 protocol. 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. However, power efficiency and real-time guarantees are two antagonist requirements in wireless sensor networks. This paper analyzes the performance of the GTS allocation mechanism in IEEE 802.15.4. The analysis gives a full understanding of the behavior of the GTS mechanism with regards to delay, throughput and power efficiency metrics. First, we propose two accurate models of service curves for a GTS allocation as a function of the IEEE 802.15.4 parameters. We then evaluate the delay bounds guaranteed by an allocation of a GTS using Network Calculus formalism. Finally, based on the analytic results, we analyze the impact of the IEEE 802.15.4 parameters on the throughput, delay and power efficiency of a GTS allocation. The results of this work pave the way for an efficient dimensioning of an IEEE 802.15.4 cluster.*

1. Introduction

With the emergence of new Wireless Sensor Network (WSN) applications under timing constraints, the provision of deterministic guarantees may be more crucial than saving energy during critical situations. The IEEE 802.15.4 protocol [1] is one potential candidate to achieve predictable real-time performance for Low-Rate Wireless Personal Area Networks (LR-WPAN). The IEEE 802.15.4 Task Group (TG4)[1], together with the ZigBee Alliance [2], has developed an entire

communication protocol stack for LR-WPAN. Although the IEEE 802.15.4 protocol was not exclusively designed for wireless sensor networks, it provides suitable mechanisms for WSN applications [3]. The physical layer of the IEEE 802.15.4 protocol seems particularly suitable for WSN applications, namely in terms of data-rate, energy-efficiency and robustness. More importantly, the Medium Access Control (MAC) sub-layer, with the provision of a superframe structure bounded by two signaling beacon frames (when in beacon-enabled mode), makes the IEEE 802.15.4 protocol sufficiently flexible and able to fulfill the needs of a large variety of applications. In fact, when an IEEE 802.15.4-compliant WPAN disables the generation of periodic beacon frames i.e. non-beacon enabled mode, all nodes in the network compete to gain access to the medium using non-slotted CSMA/CA. The advantage of the non beacon-enabled mode, with regards to WSN application requirements, is that it easily allows scalability and self organization. However, the non beacon-enabled mode does not provide any guarantee to deliver data frames, specifically within a certain deadline. For time-critical applications, real time guarantees may be achieved with the beacon-enabled mode. This mode offers the possibility of allocating/deallocating time slots in a superframe, called Guaranteed Time Slots (GTSs) and providing predictable minimum service guarantees. Having a minimum service guarantee, it is possible to predict the worst-case real-time performance of the network. This paper provides a methodology, based on the Network Calculus formalism [4], for evaluating the performance of real-time applications using the GTS mechanism in one IEEE 802.15.4 cluster. We propose two alternative models for the service curve provided by a GTS allocation, and derive the corresponding delay bounds. An expression of the duty cycle as a function of the delay bound is also derived. Additionally, analysis on the impact of the IEEE 802.15.4 parameters, namely the superframe order, on the maximum throughput, delay bound and power efficiency of a GTS allocation is also presented. To our best knowledge, this is the first work evaluating the deterministic real-time guarantees of the IEEE 802.15.4 protocol. We hope that this work provides a first step towards the practical use of the IEEE 802.15.4 GTS mechanism, and therefore providing deterministic guarantees for real-time sensor network applications.

3. Overview of the IEEE 802.15.4 Protocol

The IEEE 802.15.4 MAC protocol supports two operational modes that may be selected by a central node called PAN coordinator:

i. The non beacon-enabled mode: MAC is ruled by non-slotted CSMA/CA;
ii. The beacon-enabled mode: beacons are periodically sent by the PAN coordinator to identify its PAN and synchronize nodes that are associated with it. In this paper,

we only consider the beacon-enabled mode, since it has the ability of providing guaranteed real-time performance to the network. In beacon-enabled mode, the Beacon Interval (BI) defines the time between two consecutive beacons, and includes an active period and, optionally, an inactive period. The active period, called superframe, is divided into 16 equally-sized time slots, during which frame transmissions are allowed. During the inactive period (if it exists), all nodes may enter in a sleep mode, thus saving energy. Fig. 1 illustrates the beacon interval and the superframe structures.

The lengths of the Beacon Interval and the Superframe Duration (SD) are determined by two parameters, the Beacon Order (BO) and the Superframe Order (SO), respectively. The Beacon Interval is defined as follows:
BI= a Base Superframe Duration * 2BO
For $0 \le BO \le 14$ (1)

The Superframe Duration, which determines the length . The active period , is defined as follows:
SD = a Base Superframe Duration * 2SO
For $0 \le SO \le BO \le 14$ (2)

In Eq.(1) and Eq. (2), a Base Superframe Duration denotes the minimum length of the superframe, corresponding to SO = 0 . The IEEE 802.15.4 standard fixes this duration to 960 symbols (a symbol corresponds to 4 bits). This value corresponds to 15.36 ms, assuming a 250 kbps in the 2.4 GHz frequency band. In this paper, we will only consider the features of the 2.4 GHz frequency range, which is supported by the MICAz motes1 from Crossbow Tech. [9], for example.

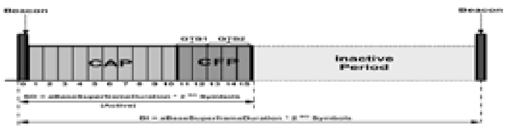

Fig. 1. Beacon Interval and Superframe Concepts

By default, the nodes compete for medium access using slotted CSMA/CA during the Contention Access Period (CAP) during SD. In case of a busy channel, a node computes its backoff period based on a random number of time slots. The IEEE 802.15.4 protocol also offers the possibility of having a Contention-Free Period (CFP) within the superframe (Fig.1). The CFP, being optional, is activated upon request from a node to the PAN coordinator for allocating time slots depending on the node's requirements. Upon receiving this request, the PAN coordinator checks whether there are sufficient resources and, if possible, allocates the requested time slots. These time slots are called Guaranteed Time Slots (GTSs) and constitute the CFP. If the available resources are not sufficient, the GTS request fails. The corresponding node then sends its data frames during the CAP. A detailed description of GTS management and of the slotted CSMA/CA mechanism is presented in [3]. SD and BI also determine the duration of the inactive period. Saving energy may be achieved by imposing large inactivity periods leading, however, to increasing communication latencies. Hence, BO and SO are key parameters for balancing the real-time performance and energy savings in IEEE 802.15.4-based networks. In this paper, we show how to find the optimal durations of SD and BI that best fit the real-time requirements of the WSN applications, while making a trade-off with energy consumption.

4.1 Problem Formulation

Let us consider an IEEE 802.15.4 cluster with a unique PAN coordinator, and a set of nodes for drip irrigation system within its radio coverage. The network operates in beacon-enabled mode, thus the PAN coordinator periodically sends beacon frames. The Beacon Interval and the Superframe Duration are defined by Eq. (1) and Eq. (2), respectively. Let C be the total data rate of the output link. In our case, the data rate is fixed to C = 250 kbps, as previously mentioned in Section 3. Each sensor node in the range of the PAN coordinator runs an application that generates a data flow. We consider that each data flow has a cumulative arrival function R(t) upper bounded by the linear arrival curve $\alpha(t) = b + r.t$ with b denoting the maximum burst size, and r is the average arrival rate (Fig. 2).

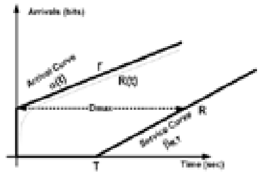

Fig. 2. Arrival Curve, Service Curve and Delay Bound

This model is called a (b, r) model. In addition to its simplicity, the (b, r) model has the advantage to represent a higher bound of any kind of traffic, rather than dealing with unrealistic assumptions on the traffic type (e.g. assuming a Poisson arrival pattern). For instance, it has been shown [10], that a periodic traffic with or without jitter can be represented with a (b, r) curve. In general, it is possible to translate any traffic type to the (b, r) model, provided that the cumulative arrival function is upper bounded. The variance between the (b,r) curve and the realistic model may be large for highly variable data rate traffic. For a periodic traffic with or without jitter, however, the variance is not too pessimistic. Since WSN applications typically generate periodic traffic, the (b,r)model is considered to be acceptable in that context.

4.2 Delay Bound Analysis using Network Calculus

Network Calculus is a theory for deterministic queuing systems [4], which provides a mathematical framework based on min-plus and max-plus algebras for delay bound analysis in packet-switched networks. The delay bound analysis approach for a given data flow with a cumulative arrival function R (t) assumes that it exists:
i.An arrival curve $\alpha(t)$ that upper bounds R (t) such that ΔS,
$0 \le s \le t$, $R(t) - R(s) \le \alpha(t-s)$
This inequality means that the amount of traffic that arrives to receive service in any interval[s, t] never exceeds $\alpha(t - s)$.
ii.A minimum service curve $\beta(t)$ guaranteed to R(t).
In that case, the delay bound, Dmax, for this data flow with an arrival curve $\alpha(\tau)$ that receives the service $\beta(t)$ is the maximum horizontal distance between $\alpha(t)$ and $\beta(t)$. Hence,

$$Dmax = h(\alpha,\beta) = \sup_{s\ge 0}\{\inf\{\tau \ge 0: \alpha(s) \le \beta(s+\tau)\}\} \quad (3)$$

Fig. 2 presents an example of the delay bound for a linear arrival curve $\alpha(t)=b+r.t$ that receives a rate-latency service curve $\beta_{R,T}(t = R(t-T)$ where $R \ge r$ is the guaranteed band width, T is the maximum latency of the service and $(x)^+ = \max(0,x)$. This service curve is typically used for servers that provide a bandwidth guarantee with a certain latency. The latency T refers to the deviation of the service (e.g. blocking factor of non-preemptive transmissions).

The delay bound Dmax (presented in Fig. 2) guaranteed for the data flow with the arrival curve $\alpha(t) = b + r.t$ by the service curve $\beta_{R,T}(t) = R(t-T)^+$ is computed as [4]:

$$D_{max} = \frac{b}{R} + T \quad (4)$$

4.3 Delay Bound Analysis for One Time Slot GTS

In this section, we derive the delay bound guaranteed for a data flow upper bounded by an arrival curve $\alpha(t) = b + r..t$ and granted one GTS slot allocation in the superframe defined by the parameters BO and SO as defined in Eq. (1) and Eq. (2). Based on the results of Network Calculus, our problem is reduced to finding a service curve$\beta(t)$ that corresponds to a GTS allocation. Then, it will be possible to derive the expression of the delay bound using Eq. (3) and Eq. (4).

4.3.1 The GTS Service Curve

Let us consider a one time slot GTS allocated to a data flow bounded by a(b, r)curve (Fig. 3).According to the standard [1], a node that has allocated a GTS can transmit a message

Volume : 3 | Issue : 2 | February 2013 | ISSN - 2249-555X

if and only if the whole transaction, including data transmission, the Intra-Frame Spacing (IFS) and the acknowledgement (if requested), can be completed before the end of the GTS. Otherwise, it must wait until the next GTS. Fig. 3 also presents the cases acknowledged and unacknowledged transactions. Hence, a given GTS allocation may impose a restriction on the frame length. Moreover, only a part of the GTS can be used for data transmission. The rest will be idle or used by a potential acknowledgement frame. The impact of a given GTS allocation on the throughput will be discussed later on, in Section 5.

For the sake of simplicity and without loss of generality, we assume one data frame transmission in a GTS. Final results are still valid from multiple data frame transmissions inside a GTS. Now, let Ts denote the Time Slot duration in the superframe. Then,

Fig. 3. The GTS Service Time and Transmission Modes

$Ts = \frac{SD}{16}$ = abaseSuperframeDuration * 2(SO-4) (5)

We define Tdata and Tidle (Fig. 3) such that:

Ts = T data + T idle (6)

Tdata defines the maximum duration used for data frame-transmission inside a GTS. Tidle is the sum of idle times spent inside a GTS due to protocol overheads (IFS and/or Ack frames). The minimum value of Tidle comprises the time required for an IFS, TIFS, and a potential acknowledgement in the case of an acknowledged transmission, Tack. Hence, the following analysis holds for both acknowledged and unacknowledged transactions. The only difference is the setting f the value of Tidle. We can write:

T idle = T overhead + T wasted
Where T overhead = TIFS + TACK.□ACK (7)

where □Ack = 1 for an acknowledged transaction and □Ack = 0 for an unacknowledged transaction. The value of wasted time, Twasted is greater than zero if the length of a GTS is longer than the transaction time (transmission + IFS + Ack). A frame of the data flow that has allocated the GTS uses the entire capacity of the output link for a time period of Tdata, every Beacon Interval BI.

a. Real service curve of a GTS
First, we need to define the maximum latency T that a burst may wait for a service. This latency occurs for a burst that arrives just after the end of the GTS. It results that the maximum latency T (Fig. 4) can be computed as:

T=BI-Ts (8)

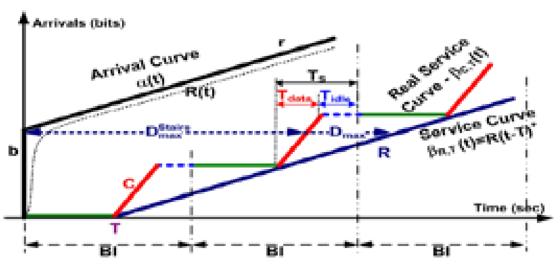

Fig. 4. The GTS Service Curves

In our analysis, we define the kth superframe as the superframe contained in the time interval

[(k -1)BI, k.BI]

In the first superframe, the service curve received by the data flow; that is, the minimum number of bits that must be transmitted during the GTS is:

$$= \begin{cases} c(t-(BI-Ts)) & 0 \le t \le BI - T\ idle \\ 0 & otherwise \end{cases}$$

β_{CT}^{stair} (t) is a stair function, which is the sum of all rate latency service curves of each superframe, and represents an overall service curve for the data flow (Fig 4)

4.4 General Case of n Time Slot GTS
The reasoning for a GTS with n allocated time slots is similar to the previous one except that the service will not be continuous due to the mandatory idle period inside each slot for IFS and acknowledgement processing. This causes a slight change in the construction of the stair service curve for an allocation of n time slot when 2 ≤ n ≤ 7 (no more than 7 GTSs can be allocated in a superframe). Fig. 5 shows an example for allocations of 1, 2 and 3 GTSs inside a superframe.
As a consequence, the guaranteed bandwidth of a GTS with n time slots is:
Rn = n.(λ.DC.C – W idle) (16)

and the latency T is then:
Tn = BI – n.TS (17)

However, in the IEEE 802.15.4 GTS mechanism, the bandwidth and the latency are correlated, since they both depend on the superframe parameters BO and SO. Hence, increasing the number of slots allocated to a GTS simultaneously increases the guaranteed bandwidth and reduces the maximum latency, leading to a lower delay bound.

5. Impacts of the Beacon and Superframe Orders On the Maximum Throughput of a GTS
5.1 Problem Statement
According to [1], it is possible to transmit more than one frame inside one allocated GTS. The only restriction is that the transactions (including IFS and acknowledgement if required) must complete before the end of the GTS. However, when the superframe order is incremented by one, the time slot duration is doubled. From a given superframe order, it is not be possible to use the entire duration of the time slot for data frame transmissions. This leads to an under utilization of the GTS. This is due to two factors:

- The maximum burst size of a data flow is bounded by the maximum memory size of a node. It is not possible to store a bulk of data more than the capacity of the memory.
- The arrival of data frames from higher layers (application) is most often with low rate. More formally, for a data flow with an arrival curve α(t) = b + r . t the burst size b cannot exceed the memory size of the sensor node, and the average arrival rate of the data flow r, is assumed to be low.

On the other hand, the duration of one time slot for a superframe order SO = 10 is approximately equal to one second, which corresponds to send at most a bulk of 208 (aMaxPHYPacketSize2 bits long) unacknowledged frames (~ 211 kbits) with a long IFS. However, due to sensor node resource limitations (processing and memory) it is unpractical to assume that a sensor node has the ability to generate 211 kbits of data during one second, due to the limitation of the arrival curve. For instance, a sensor node that generates traffic with a maximum burst size of 32 kbits, and an average arrival rate of 10 kbits/sec cannot produce more than (32 kbits + (10 kbits/sec. 1sec)) = 42 kbits during one second. Hence, the amount of effectively used bandwidth does not exceed 42 kbits/sec, which corresponds to a throughput of around

Volume : 3 | Issue : 2 | February 2013 | ISSN - 2249-555X

20% considering the previous scenario. The purpose of this section is to evaluate the maximum throughput that may be achieved by a GTS for different values of the superframe order SO. We show how the burst size and the arrival rate affect the throughput for high superframe orders.

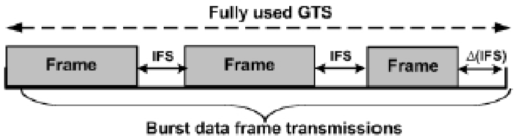

Fig. 6. Fully used GTS

The maximum throughput in this case depends on the maximum number of data frames, denoted as N, that may be sent during the GTS. This number depends on whether the frames are sent with a SIFS or LIFS intra-frame spacing's. Hence, we consider two cases for evaluating the maximum throughput for multiple transmissions:

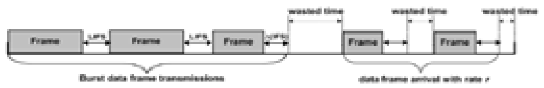

Fig. 7. Partially used GTS

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Multiple frames are transmitted with the maximum frame length, aMaxPHYPacketSize, therefore separated by LIFS periods. Then, the maximum number of frames that can be transmitted is:

$$N_{LIFS} = \left\lfloor \frac{Ts}{aMaxPHY\ packetSize + LIFS} \right\rfloor + 1$$

b. The burst size is lower than the GTS duration

In this case, the GTS is partially used, as shown in Fig. 7.

The maximum throughput in this case depends on the maximum number of data frames, denoted as N, that may be sent during the GTS. Since the arrival is bounded by the curve α(t) = b + r . t, thus no more than α(t) = b + r . Ts can arrive and be transmitted during the GTS.

On the other hand, in general, for high values of r (close to the link capacity C), the amount of bits carried by α(t) may be higher than what can actually be transmitted during the GTS when it is fully used, which is equivalent to the previous case. Hence, Tdata is always lower than .

T_{data}^{full} Now, in general, we have:

$$T_{data} = min\left[\begin{array}{c} \frac{b + r.Ts}{C} \\ max\left(\begin{array}{c} Ts - (N_{LIFS} - 1).LIFS - \Delta(IFS) \\ Ts - N_{LIFS} .\ SIFS \end{array} \right. \end{array} \right. \quad (26)$$

As a result, the maximum throughput is:

7. Power Efficiency of GTS Allocation

7.1 Problem Statement

At start-up, the PAN coordinator of a given WPAN cluster must choose a superframe structure. The choice of the superframe structure affects the timing performance as well as the energy consumption in the cluster. Saving energy requires superframe structures with low duty cycles, whereas improving the timing performance requires higher duty cycles. A trade-off must be achieved by choosing the lowest duty cycle that still satisfies the timing constraints of the data flow. In this study, we consider data flows with a common arrival curve and the same delay requirement. This assumption can hold for many wireless sensor network applications, since the data sent by sensor nodes are related to common observed phenomena, and thus data flows are closely similar. In case the arrival curves are different from one application to another, we consider the data flow with the highest burst size and the lowest delay requirement for that worst-case dimensioning of the system.

7.2 Duty Cycle Evaluation

Note that each data flow allocating a GTS with the above requirements must adapt its arrival rate to the amount of bandwidth guaranteed by their GTS corresponding to the combination of SO and BO, based on Eq. (14). Stating that the combination of SO and BO simultaneously satisfies the delay requirement D and reduces the energy consumption is equivalent to state that the corresponding duty cycle DC=2SO-BO is the lowest one that satisfies the delay requirement D. In what follows, We envisage to express the duty cycle as a function of the delay.

The duty cycle can be expressed as a function of the delay as follows:

$$DC = \frac{SD}{D + \lambda.\ SD} \cdot \left\{ \frac{b}{Tdata.C} + 1 \right\}$$

where SD is the Superframe Duration (Eq. 2).

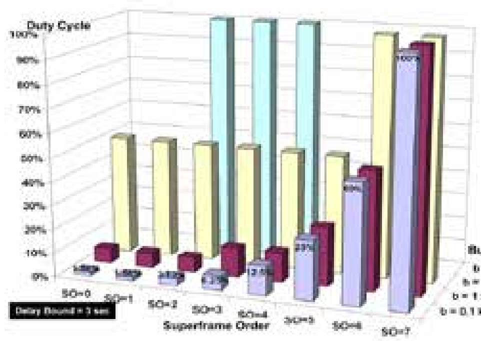

Fig.8 Duty Cycle Vs Superframe Order

8 Conclusion

In this paper, we have proposed a methodology for drip irrigation system analyzing the Guaranteed Time Slot mechanism provided by the IEEE 802.15.4 protocol. Using Network Calculus formalism, we have proposed two accurate models for the service curve provided by a GTS allocation and derived the delay bounds guaranteed by such an allocation. An expression of the duty cycle as a function of the delay was also presented. Based on those results, the impact of the beacon order and the superframe order on the maximum throughput, delay bound and power-efficiency was analyzed. In summary, for WSN drip irrigation system applications typically with low arrival rates and low burst size, using low superframe orders is more convenient for providing low delay bounds. However, they lack of efficient utilization of the GTS capacity due to their short duration and to the impact of IFS. It has been also shown that, low superframe orders are more power-efficient while still satisfying a given delay bound requirement.

We hope that this work provides a first step towards the efficient use of the GTS mechanism in IEEE 802.15.4- compliant networks such as drip irrigation system.

Volume : 3 | Issue : 2 | February 2013 | ISSN - 2249-555X

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