Modelling, Verification and Validation of the IEEE 802.15.4 for Wireless Networks

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Abstract. The purpose of this paper is to present a model of an mechanism Carrier Sense Multiple Access - Collision Avoidance unslotted capable of accessing the environment. This mechanism is utilized in the latest IEEE 802.15.4 standard, which defines the wireless Medium Access Control and the Physical layer-specification for Low-Rate Wireless Personal Area Networks. For the model construction, Hierarchical Coloured Petri Nets will be used. Hierarchical Coloured Petri Nets are extensions of Coloured Petri Nets. Design/CPN tools will be used for simulations, and the model will be verified and validated by means of occurrence graphs generation.

1 Introduction

The Low-Rate Wireless Personal Area Networks (LR-WPAN) is a new default in wireless networks developed by the Institute of Electrical and Electronic Engineers (IEEE) and the National Institute of STandards (NIST) to transmit information to short distances at a low rate. The LR-WPAN operates within a Personal Operating Space (POS) of 10 m or less. The LR-WPAN makes use of data rate of 20 Kb/s and an upper bound of 250 Kb/s [1].

The LR-WPAN specified by IEEE 802.15.4 standard, is used for low cost equipment with serious restrictions as to power consumption, the operation of which does not require high rate transfers [2, 3].

The IEEE has, recently, defined a group of established smart sensor interfaces with the IEEE 1451.5 specifications [4]. Such specifications adopt both the ZigBee association and the IEEE 802.15.4 technology in sensor networks applications for wireless communication. The 802.15.4 technology defines the physical layer and the link layer, whereas the grouping ZigBee defines the network and application layers [5].

The fast progress in the field of microprocessors, new monitoring sensors, Micro-ElectroMechanical System and wireless communication have fostered the development

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and application of LR-WPAN in areas related to physical, chemical and biological processes, among others.

Due to these limitations, the search for new protocols and techniques has greatly increased, and has become an enormous challenge in this area. Such developments, however, require a test network that, in most cases, is not feasible from an economic viewpoint owing to the fact that these networks are made up of hundreds, sometimes, thousands of very expensive sensor units.

Based on what has just been said, the construction of a computational model in order to support both the reduction in power consumption and the optimization process has become of crucial importance in terms of costs and complexity.

It will be presented in this paper a model analysis of the IEEE 802.15.4, mainly the link layer, by means of an access protocol to the Carrier Sense Multiple Access - Collision Avoidance (CSMA-CA) unslotted environment. Nevertheless, few are the methods for simulating, verifying and validating such systems. Among these methods, one can find the hierarchical coloured Petri nets. Hierarchical Coloured Petri Nets (HCPN) are very much useful for modelling dynamic and concurrency systems, such as a wireless sensor network.

The remaining sections of this paper have been organized as follows: Section 2 gives full details of the mechanism CSMA-CA unslotted ; Section 3 presents a brief description of HCPN; Section 4 describes our Mechanism CSMA-CA unslotted HCPN model; Section 5 presents an analysis of the model; and Section 6 exhibits the conclusions and points towards further developments.

2 Defining the Mechanism CSMA-CA

The CSMA-CA mechanism is utilized in various network technologies, especially in wireless technologies (e.g. in IEEE 802.ll and 802.15.4). This is a contention based-mechanism that attempts to avoid a collision situation in the network by checking the channel before transmission. Should the mechanism find the channel busy, a random time, termed backoff, is then devised so as to try again until it accesses the channel; either by reaching or even exceeding the backoff. In such cases, transmission fails, and the frame is retransmitted [5].

The CSMA-CA algorithm cannot be used for beacon frame transmissions, acknowledgement frames or data transmitted over a Contention-Free Period (CFP). The LR-WPAN employs two different kinds of mechanism in order to access the channel: the CSMA-CA slotted or the CSMA-CA unslotted; the CSMA-CA slotted being out of the scope of this paper. Further information regarding this mechanism can be found in [1].

For the mechanism LR-WPAN unslotted, any devices in need of transmitting data or Medium Access Control (MAC) commands must wait for some random time. Transmission will only be possible when the channel becomes free after the backoff; otherwise, the device will create another backoff and attempts to access the channel once again. Such procedure will be repeated until the channel is accessed, or until waiting upper limits are achieved. Further details about these limits will be given later in this paper.

Figure 1, redrawn from [1], shows the CSMA-CA unslotted algorithm, where variables NB (Number Backoff (periods)) and BE (Backoff Exponent) are initialized in

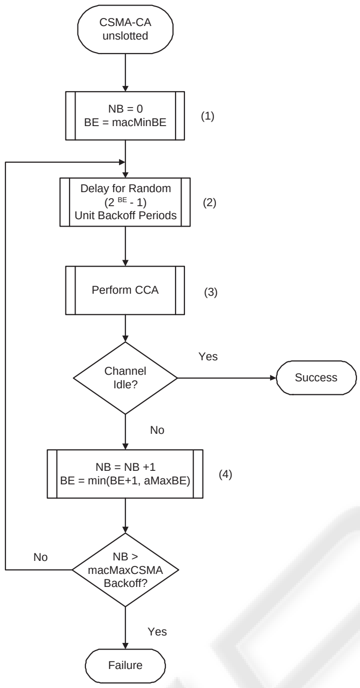

Fig. 1. The CSMA-CA unslotted algorithm

step 1, with the values zero and $macMinBe$, respectively. The $macMinBe$ exhibits value 3 as default. After completion of step 2, the backoff calculation is carried out. This can vary from zero to $(2^{BE} - 1)$ backoff units, a value that is defined by variable $aUnitBackoff$ period with a default value that equals 20.

Step 3 provides for the Clear Assessment (CCA). Here one verifies whether the channel is capable of transmitting data successfully. If otherwise, step 4 will be taken, where the NB and BE values are applied in 1. However, BE values should not be greater than $aMaxBE$, whose default value is 5. Still in step 4, one verifies if the NB value is greater or equal to the $macMaxCSMABackoff$, which has the default value for 4. If so, transmission is aborted, or returns to step 2.

CCA represents the waiting procedure defined by the backoff, which comes as a result of the channel propagation delay, transmission delay, and other parameters, depending on the physical environment. Further details can be found in [1].

3 Coloured Petri Nets Introduction

The basic foundation used for the modelling is that of the Hierarchical Coloured Petri Nets, which is a Coloured Petri Nets extension [6]. HCPN is a suitable modelling language used for task verification, for they can express concurrency, parallelism, non-determinism and different levels of abstraction needed by the channel access mechanism, e.g. CSMA-CA unslotted [7]. The HCPN considers modelling at hierarchical levels. This has been made possible by the inclusion of two mechanisms: the substitution transition, and the fusion places. A substitution transition is a transition that can be replaced by a CPN page [6].

Modelling requires a set of computational tools for editing, simulation and analysis. The Design/CPN [8] consists of a package of four computational tools for developing hierarchical coloured Petri nets.

4 HCPN Model of Mechanism CSMA-CA Unslotted

The HCPN model of mechanism is described in 3 pages that models the mechanism. There is still another page that defines the types, data structures and the functions needed to secure its perfect functioning. The model global declarations encompass the types and variables of the mechanisms CSMA-CA unslotted.To follow a summarized description of these paginas will be made.

4.1 Declarations

The model global declarations encompass the types and variables of the mechanisms CSMA-CA unslotted. Figure 2 shows all the types and variables of the model, described as follows: **BE**, Backoff Exponent is the exponent used to calculate the CSMA-CA Backoff period;**VB**, value Backoff is used to store the calculated value from BE and from the random period;**NB**, number Backoff is used to control most backoff numbers resulting from each transmitting cycle.

The CSMA-CA holds 4 constants that are initialized with values defined by the IEEE 802.15.4 standard [1]. These are: **macminbe** which is the minimum value of BE in the CSMA-CA algorithm; **macMaxCSMABackoff** which is the maximum number of backoff; $aUnitBackoffPeriod$, which is the number of symbols forming the basic time period used by the CSMA-CA algorithm and **amaxbe** is the maximum value attributed to the BE variable.

For the backoff calculus, a random number generator is specified by means of the following variables: $be3$, $be4$ and $be5$, which are responsible for creating radom number.

4.2 Mechanism CMSA-CA Unslotted

Figure 3 shows the modelled mechanism CSMA-CA unslotted. The maximum verification limit ($macMaxCSMABackoff$) is carried out by this model by means of transitions $NBValid$ and $NBInvalid$, where these have the guards $[nb <> 4]$ and $[nb = 4]$, respectively. If the limit is reached, as one can see in the algorithm shown in Figure 1, a transmission failure is then detected, in which case, the sensor is re-initiated. This is accomplished by the arc inscription of the $ReSend$ ($1`(sensor, 3, 0, 0)$)transition, after which the verification is transmitted again; or else, the backoff calculus proceedings are called forth by means of the $CallBO$ place, which binds with the $StartBO$ place, as modelled in the $BackOffCalc$ subpage, shown in Figure 4.

```
(* Global Declaration *)

color Sensor = with sensor1 | sensor2;
color Status = with livre | ocupado;
color Contador = int;
color BE = int;
color VB = int timed;
color NB = int;
color Tabela = product Sensor * BE * VB * NB;
color Relogio = product Status * Contador * Sensor * BE * NB timed;
var sensor:Sensor;;
var status:Status;
var cont:Contador;
var be:BE;
var vb:VB;
var nb:NB;

(* MAC SubLayer Constant  *)
val macMaxCSMABackoff = 4 : int;
val macminbe = 3 : int;
val amaxbe = 5 : int;
val aunitbackoffperiod = 20 : int;

(*Constant of Calculate Backoff *)

color Int_0_7 = int with 0..7;
color Int_0_15 = int with 0..15;
color Int_0_31 = int with 0..31;
var be3:Int_0_7;
var be4:Int_0_15;
var be5:Int_0_31;

( * Function for Calculate OG *)

val gettimeofday : unit -> (Int32.int * int) =
    Unsafe.CInterface.c_function "SMLNJ-Time" "timeofday"

fun tod() =
  let
      (* max int in SML on 32 bit machines (see Int.maxInt) *);
      val maxint31 =  Int32.fromInt 1073741823

      val (secs, _) = gettimeofday()

      (* convert back into "small integers" to preserve type *)
      val secs31bit = Int.fromLarge(Int32.-(secs,maxint31))
  in
    secs31bit
  end;
```

Fig. 2. Colors Sets and Variables

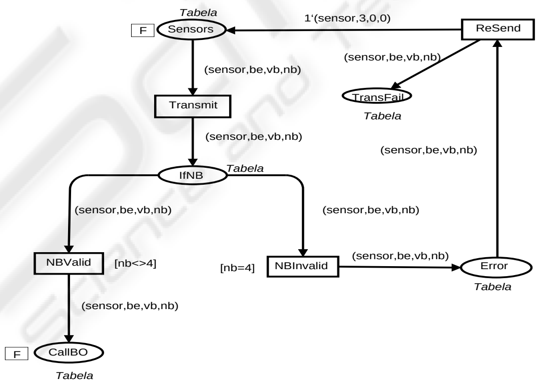

Fig. 3. CPN Model for CSMA-CA.

When simulation is completed, one can see, on the final marking at $TransFail$, the number of sensors that exceeded the backoff maximum limit, and as a result, had to initiate a re-transmission. It is on this page that sensors are inserted into our model, mainly, on account of the initial marking of the $Sensors$ place. Once sensors are defined, transmission is carried out with success bringing simulation to an end in a case where no feedback was needed.

The fusion place of the $CSMA{-}CA$ page was obtained through an $AccessChannel$ subpage whose description can be found in Section 4.4. This will supply this page with the sensors' traffic. The latter will find the busy channel after a backoff initial period.

4.3 BackOffCalc

The $BackOff$ page, shown in Figure 4, models the backoff calculus procedure. This page is summoned by $CSMA - CA$ page from which it obtains the sensors' traffic, going through steps 1, 2 and 3 of the algorithm shown in Figure 1. The $CaseBE$ and $CompBE$ transitions arcs work out the BE calculus and determine the random waiting value. Both are shown in step 2 of Figure 1. After calculating the random time period, the model uses up its time through the expression $@{+}vb$, which is the $StarTime$ transition guard. The backoff calculus procedure is completed in the $SendAccChann$ place, which is the fusion place with the $AccessChannel$ page. This page will be described in Section 4.4.

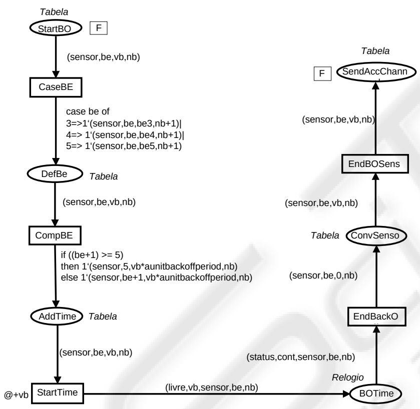

Fig. 4. CPN Model for BackOffCalc.

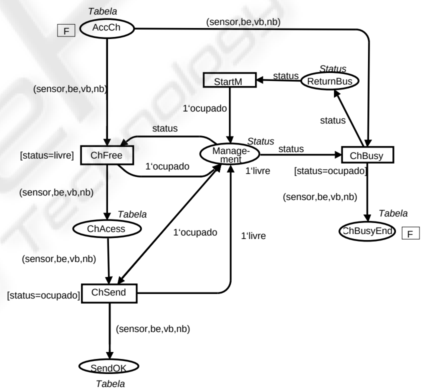

Fig. 5. CPN Model for AccessChannel.

4.4 The AccessChannel

The $AccessChannel$ page, described in Figure 5, is executed whenever a sensor attempts to access the channel after a backoff period. The $AccCh$ place provides the sensors' traffic, which is the fusion place with the $SendAccChannel$, as illustrated in Figure 4. Here, the model checks if the channel is available by means of a $CHFree$ transition with the guard $status = free$. Once the channel's availability is attested, the simulation procedure starts with the free set given by the $Management$ place initial marking, as shown in Figure 5. With the occurrence of $CHFree$ transition, a token with a status that says $busy$ in the $Management$ place, will be positioned. The $ChBusy$ transition is then enabled, owing to its guard ($status = busy$). The channel remains busy until a $ChSend$ transition fires, indicating end of transmission.

On the other hand, whenever the $ChBusy$ transition is enabled, it means that there exist transmitting sensor and that the channel ($ChFree$) is busy. In case one gets a $ChBusy$, a token is then positioned in the $ChBusyEnd$ place. As a result, a new backoff calculus is needed, as this is the fusion place with $StartBO$, as illustrated in Figure 4.

This page models a situation that is common to occur with the mechanism CSMA-CA unslotted, which is a sensor to transmit and detect the busy channel. The NB is then increased to 1, being necessary to re-calculate the backoff period, as described in step 4 in Figure 1, and to model it on the $BackOffCalc$ page (Fig. 4).

5 Model Analysis

For the model analysis, different scenarios have been considered in order to verify the properties and to validate them in relation to the mechanism CSMA-CA unslotted. The scenarios are established by the quantity of sensors defined in the model. However, for these scenarios, two, ten and twenty sensors are taken into account. The Sensors place initial marking corresponds to the number of sensors, as shown in Figure 3. The model gets to its final state when all sensors, specified in the initial marking, reach the $SendOk$ place, as shown in Figure 5. It must be noticed that different markings may be admitted to the final state, because a token can be represented by the color, and these may assume different values in accordance with backoff value.

```
Statistics
----------------------------------------------------------
Occurrence Graph
Nodes:18448 Arcs:31036 Secs:18301 Status:Full
Boundedness Properties
----------------------------------------------------------
Best Integers Bounds  Upper   Lower
 CSMA'AccCh 1           2       0
 CSMA'AddTime 1         2       0
 CSMA'ChAcess 1         1       0
 CSMA'DefBe 1           2       0
 CSMA'Error 1           1       0
 CSMA'IfNB 1            2       0
 CSMA'Management 1      1       0
 CSMA'ReturnBusy 1      1       0
 CSMA'SendOK 1          2       0
 CSMA'Sensors 1         2       0
 CSMA'Time 1            2       0
Liveness Properties
----------------------------------------------------------
Dead Markings:1400 [9986,9945,..]Dead Trans.Instances:None
```

As one may have noticed before, by means of occurrence graphs, it is possible to verify the properties inherent to the model. Occurrence graphs are directed graphs that can present a node for each reachable marking and an arc for each binding element. An arc binds the marking node, here the associated binding element comes from the resulting marking node of occurrence.

The Design/CPN graph tools will permit report emission with the general properties of the model. This report contains information on the graph and on the properties that are useful to understand the model's behavior in HCPN.

Considering the scenario for two sensors, the report sent with the general properties contains the node number, arc number, and the time needed for its full generation. The scenario for two sensors, considered in the occurrence graph, follows as a result of this, regarding all possible sequences including the concurrency between sensors so as to access the channel. Should one consider only one sensor, some dead transition instances will be identified, in which case there will be no concurrency.

As for the boundedness properties, it is important to show the following places: $Sensors$, $SendOK$ and $ChAccess$. For the $Sensors$ place and $SendOK$ the upper and lower bounds are two and zero, respectively. These places represent the number of sensors in the scenario. The upper bound to the place $ChAcess$ is one, since this place illustrates the channel, and only a sensor can access the channel.

With the liveness properties, described in the report, one can verify the absence of dead transitions instances. For such, the number of dead markings is identified as a state explosion, due to the acceptable backoff number. This is shown in Section 4.

With the various simulations covering the scenarios two, ten and twenty sensors, one may deduce that the model presents only correct end states and deadlock free. The correct end states are illustrated by the $SendOK$ place, shown in Figure 5, where all sensors for the final simulation are to be found.

The properties considered above are significant for validating the model, for the channel represented by the $ChAccess$ place can only have one sensor at a time. The $SendOK$ shows the sensors that were successfully transmitted.

6 Conclusions

The main contribution of the present research is the setting up of a formal model definition, using Coloured Petri Nets for the IEEE 802.15.4 Link Layer. By means of this model, it will be possible to develop techniques for the reduction of power consumption and for the optimization process.

The model we propose to represent such standard proved to be coherent. The model was checked by means of an occurrence graph tool through which each place maximum and minimum markings were obtained. It was also possible to investigate transmission failure occurrences by a final marking of the $TransFail$ place, i.e. when a sensor attempts to access the medium four times over, only to find it busy. The model validation is obtained by the final marking of the $SendOK$ place. At the end of simulation, all items specified by the initial marking must be presented this place, in spite of the fact that some attributes may exhibit different values. By means of these values, it is possible to verify the network loading state.

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