Global generic model for formal validation of the wireless sensor networks properties

Sajeh ZAIRI *, Eric NIEL ** Belhassen ZOUARI ***

* *LIP2 Laboratory, University of Tunis El Manar, 2092 Manar II, Tunis(ia) (e-mail: sajeh.zairi@fst.rnu.tn, belhassen.zouari@fst.rnu.tn).*
** *AMPERE Laboratory, INSA-Lyon, University of Lyon, France (e-mail: sajeh.zairi@insa-lyon.fr, eric.niel@insa-lyon.fr)*

Abstract:
Formal modelling techniques can be used for the analysis of wireless sensor networks (WSNs). High level Petri nets (HLP-nets) that is an extension of Petri nets is a powerful modelling technique. This paper presents a HLP-nets based approach for formal modelling and analysis of WSNs. The proposed model uses the hierarchical modelling capability of HLP-nets, including different levels of abstraction. The proposed HLP-net model is quite general and generic to present a large class of WSN behaviour. It globally models the behaviour of all the WSN's components (nodes and bases station). The designer can choose the specific level of abstraction. The interfacing of the HLP-net models representing the node operations is made through the model semantics and the fusion places (where anything that happens to each place also happens to all the other places). No additional efforts must be done to synchronise all component's models.
Add to the simulation possibility, formal verification of the network properties is also enabled based on the proposed HLP-net model. Such feasibility represents one of the major difference distinguishing the proposed method of all the existing simulators dedicated to WSNs.

Keywords: Dynamic modelling, Petri-nets, Formal verification, Hierarchical systems

1. INTRODUCTION

Wireless sensor networks (WSNs) are becoming increasingly prevalent in a wide range of domains from surveillance [Vicaire et al. (2009)] to monitoring temperature, humidity, and other environmental parameters [Mainwaring et al. (2002)].

WSNs consist of a set of small, cheap, and low-power sensor nodes that use wireless technology for communications. Comparing to other kind of networks, WSNs have some notable limitations, such as processing ability, memory capacity and battery lifetime. As a result of these limitations and the requirements for some new protocols, much research is engaged in this field.

A WSN is a quite complex computer system, thus it is hard to guarantee its correct behaviour. In most cases, accurate modelling methods need to be developed to enable rapid exploration and validation of the system design before deployment. The general approach for analysis of WSNs is to use the existing simulators. For using these tools, we must consider that the result of simulating an algorithm may be different, depending on the selected tool, because of important divergence between simulators. Employ formal modelling and analysis techniques are other alternative to simulation. Using these techniques, both performance evaluation and model checking can be applied.

To observe the correct behaviour of the system and particularly the WSN's lifetime, we need a global system model representing the different layers and protocols integrated at each node. High level Petri nets (HLP-nets) [RdP (2004)] which are an extension of Petri nets, are an appropriate modelling language. HLP-nets have a graphical notation that is based on an underlying mathematical definition and provide several analysis methods, including simulation, state space and invariant analysis. A major benefit of using HLP-nets is to obtain complete and unambiguous specifications of system behaviour.

Based on a scrupulous observation of the node's comportment, we show that they follow the same ***generic*** behaviour. Such behaviour includes : monitoring and collecting data, assessing and evaluating the information, formulating meaningful user displays, and performing decision-making and alarm functions.

This paper focus on the formal modelling and validation of the global behaviour of the studied WSN based on a HLP-nets model. Such model has the following objectives:

- representing all elements composing the WSN components using the same formalism: the application, the protocols, the interaction with the environment and an abstraction of the energy consumption model.
- defining a clear operational semantics of the modelling formalism.
- defining an easy modular building of the complete model representing the global WSN comportment.

The remain of the paper is organised as follows: Section 2 provides a survey of existing approaches dedicated to the validation of WSNs and particular works based on Petri nets. Section 3 presents the proposed HLP-net model representing the behaviour of a generic WSN. Section 4 lists the possible uses of the HLP-net model. Section 5 concludes.

2. RELATED WORKS

Due to the increasing sophistication of the algorithms dedicated to WSNs and the difficulty of modifying an algorithm once the network is deployed, there is a clear need to validate system performance or functionality prior to implementing such algorithms [Olveczky and Thorvaldsen (2006)].

Different works have used simulation (NAB (2004), Titzer (2005), Polley et al. (2004), Levis et al. (2003)) to enable rapid exploration and validation of system designs before deployment.

The formal validation of the system performance was also considered by existing works. Based on the considered requirements (performance evaluation or model checking purposes), a specific modelling technique has been selected and employed. Petri nets was one of the adopted techniques in the modelling of WSNs. Some new extensions of Petri nets were also proposed for these purposes, which use some extra information in places [Luo and Tsai (2005)] or dynamic configuration capability [Graff and Giardina (2005)] in Petri nets structure. Such extensions, attempt to extend Petri nets to model dynamic behaviour of WSNs, such as mobility of nodes, node death (as a result of battery limitation) or node failures.

The problem is that most of existing works have considered specific modelling problem. Generally, they represent the behaviour of a specific protocol (routing, MAC,...). For example, [Zhenhua et al. (2008)] employs coloured Petri nets (CP-nets) to model and analyse EEDMC routing protocol. The model seems to be an ordinary Petri net without any exploitation of the CP-nets power to obtain more compact model.

The work of [Shareef and Zhu (2008)] presents a Petri net modelling the energy consumption of a processor in WSNs. The experimental results, presented in this work, indicate that the Petri net is a better method of modelling processors than using Markov model. This is due to the fact that Markov model cannot handle fixed deterministic rates. Any change to the model can be easily made to a PN, while Markov model will require re-derivation of the equations.

A programming model build using e-Petri net, an extention of Petri nets, was proposed in [Mallikarjuna and Janakiram (2007)]. Proposed model gives the flexibility in understanding and analysing the application before the deployment of the WSN.

[Kuo and Siao (2009)] present a decentralised Petri net based wireless sensor node architecture (PN-WSNA) to construct a flexible and reconfigurable WSN for intelligent monitoring systems.

To the best of our knowledge, there is a unique approach for the formal and global modelling of the WSN behaviour: GLONEMO [Samper et al. (2006)]. GLONEMO is a formal approach including various levels of abstraction. The formalism is made of communicating parallel interpreted automata. In this case, each component of the node is modeled by a specific automaton. Automaton modelling the global behaviour of a node is obtained by composing those representing the behaviours of its components. Global automaton modelling the behaviour of the global WSN is obtained by composing as much automata as considered nodes. Signals are used to synchronise automata, according to the synchronous broadcast communication mechanism.

In addition to its difficulty, composing a large number of automata can lead to a loss of information (details). The designers must also choose the correct composition function which is not evidential for non specialists. Such model is also limited by the state explosion problem. To avoid such problems, we present a formal model representing the WSN behaviour based on HLP-nets. The use of HLP-nets allows to define a generic model representing the behaviour of a specific component (node or sink). The global model of the studied WSN is obtained be instantiating the HLP-net model of these specific components. Such initiation is made using the initial marking of a subset of places. Using such approach, interfacing (synchronising) all the models, representing the behaviour of the WSN's components, is directly made based on the HLP-net model semantic. No more efforts must be achieved to compose the different models representing the behaviours of the WSN's components. Thus, any information is lost when generating the global model.

3. HIGH LEVEL PETRI NETS MODEL

Before introducing the HLP-net model, we present the faced challenges and the correspondence between the application and the Petri net entities.

3.1 Challenges in modelling the behaviour of a WSN

The following challenges need to be addressed to build correct model representing WSN behaviour:

- ***Uniform model for different applications:*** The model should be able to express different kinds of applications such as weather prediction, habitat monitoring, etc.
- ***Capturing WSN properties:*** Some of the important propertie, associated with the node and the WSN behaviour, to be considered are: energy, localisation, temporal, dependencies and probabilities.
- ***Abstraction of WSN entities:*** One should be able to abstract the different entities composing the WSN.

3.2 Petri net extentions

Classical Petri nets only capture dependency properties. They was extended to model temporal, probabilistic, and spatial properties. Such Petri net extentions compose the HLP-nets and include:

- Coloured Petri nets (CP-nets) associate colour to each token distinguishing one token from the other. Different types of data manipulated in WSNs can be modeled based on this properties. For example, detected event, location data, energy of nodes, computation cost, energy consummed by each operation etc. can be captured by coloured tokens.

For example, consider the colour class Sensor×Energy and the associated token (1,200). In this case, we can say that node having identity *1* has an energy rate equals to *200*.

Using CP-nets all particular nodes specifies can be encapsulated through coloured tokens.

- Timed Petri nets allow to model timed information related to the activities of the WSN's components. Delay between the events/tasks, or the delay before the occurrence of an event or completion of a task, etc. can be specified based on this extention. Such delay may be deterministic and/or probabilistic.
- Pre and post conditions at the places enforce the thresholds (conditions) of the events or tasks of the considered application. For example, checking for the threshold values of detected temperature before notifying an alarm message may be modelled through the pre and post conditions.
- Tasks/events can have different priorities according to the associated layer. Such priorities can remove the conflicts while notifying events. Inherently, Petri net model defines the dependencies among the different events/tasks.
- Hierarchical HLP-nets allow to divide the model into modules small enough to keep track of. Such a module is called a submodel. This facility allows the construction of a large model as a set of smaller models connected to each other using well-defined interfaces (substitution transitions and fusion places). The obtained global model will be more readable where submodels can be modified or changed independently of the upper module. Abstracted model will be made by a subset of a substitution transitions. A downer HLP-net will be associated with each substitution transitions to model its achievement.

3.3 HLP-net model for WSN

In this section, we assume that the reader is familiarised with the HLP-net concepts.

The main objective of this work was the development of a global formal model representing the behaviour of a WSN. The obtained model allows formal validation of the network properties before its deployment.

When observing a WSN, we distinguish two different generic components : nodes and base stations (also called sink). Each of these components has a generic behaviour that can be modelled using an **hierarchical** HLP-net.

A generic behaviour of a node includes:

- the collection of the relevant quantities,
- the treatment of the collected data and the decision to transmit data considering the specified thresholds,
- the determination of the optimal transmission paths connecting each node to the base station (in proactive or reactive way). In this work, the nodes use the routing protocol that we have already presented in [Zairi et al. (2008)].
- the decision to stay active while maintaining the coverage of the target area. The considered protocol to schedule the activity of the nodes was presented in [Zairi et al. (2009)].

A generic behaviour of a sink includes:

- the treatment of received data and decision making,
- for periodic synchronous WSN, the transmission of specific message to indicate the beginning of a new round. This message can also be used to periodically initiate the configuration of the WSN as for example the determination of the optimal paths.

The presentation of the proposed approach to the global modelling of the WSN will be introduced in the next sections through an example of WSN dedicated to forest fire using specific routing and activity scheduling protocols. Selected application and protocols are only introduced for the illustration of the HLP-net model. All presented modelling specificity are fairly general as they can be applied to other WSN applications and protocols.

Developed HLP-net was made using the environment CPN Tools [Ratzer et al. (2003)].

HLP-net modelling the behaviour of nodes According to the previous presentation, the HLP-net modelling the generic behaviour of a node will include four substitution transitions. Figure 1 represents the upper layer of the hierarchical HLP-net modelling the generic behaviour of the node. Each substitution transition models a specific function of the node's behaviour.

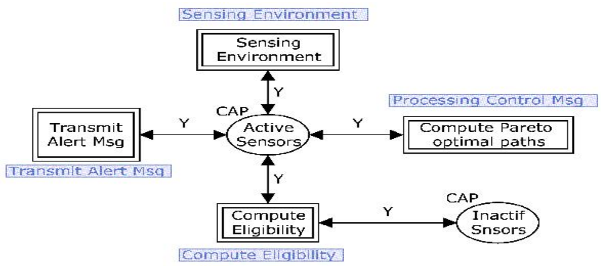

Fig. 1. The HLP-net "Sensor node"

- the substitution transition *"Sensing Environment"* models the regular monitoring of the environment,
- the transmission of the alert messages is represented by the substitution transition *"Transmit Alert Msg"*,
- the determination of the optimal transmission paths is modelled by the substitution transition *"Compute Pareto optimal paths"*.
- the substitution transition *"Compute Eligibility"* models the scheduling of the nodes activities. Eligible nodes can enter sleep state.

The tokens of the place *"Active Sensors"* define the active nodes which are able to perform any of their generic functions. However, the tokens of the place *"Inactive Sensors"* represent the inactive nodes. These tokens can not enable any of the substitution transitions. Indeed, when a node is inactive it does not perform any activity.

A subnet is associated with each substitution transition to detail the achievement of the corresponding operation. This subnet will depend on the used protocol. Specific input and output interfacing places will have generic representation regardless of the chosen protocol.

The subnet associated with the substitution transition *"Sensing Environment"* is represented by figure 2. Each node periodically senses the temperature of the environment covered by its sensing area.

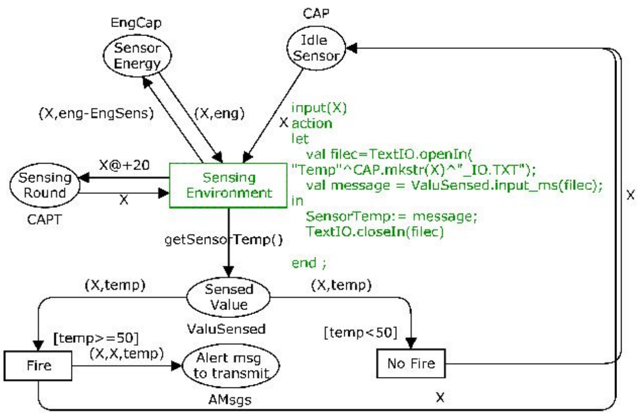

Fig. 2. The subnet "Sensing Environment"

The periodicity of this operation is represented by the timed place *"Sensing Round"*. In this case, the delay of each round is deterministic and equals to 20 time units. Such delay may also be probabilistic and function of any specific element. In the proposed HLP-net, the measurement of the temperature value is modeled by an access to an external file. This design choice allows to synchronise the proposed model with any other model representing the environment behaviour.

After data detection, the node must decide if data must be send or not to the sink. For the considered application sample, two cases can occur, according to the measured temperature:

- the measured temperature is lower than the specified threshold; no fire is detected. In this case, the node returns immediately to its idle place; firing the transition *"No Fire"*. The verification of the threshold is modelled through the guard ($temp < 50$) associated with the transition *"No Fire"*.
- the measured temperature is greater than the specified threshold; a fire is detected. After placing a token representing the alert message, which must be transmitted to the sink, in the mailbox (place *"Alert msg to transmit"*), the node returns to its idle place.

A token modeling an alert message is a 3-tuple and defines:

- the destination of the message. The identity of the relay node for which the message is transmitted.
- the origin of the alert. The identity of the node that has detected the fire.
- the value of the measured temperature in the fire area.

Alert messages will be transmitted by relay nodes until their reception by the base station. The token placed in the mailbox place *"Alert msg to transmit"* (which is a fusion place) enable the substitution transition *"Transmit Alert Msg"* modelling the transmission of messages. As in the considered example, the transmission of message is done in multi-hop, the substitution transition *"Transmit Alert Msg"* will be enabled until the message will be received by the sink.

Each subnet modelling a specific node operation include an energy place (*"Sensor Energy"* which is a fusion place). At any time, the tokens of this place associate the residual energy with each node. Residual energy is modified any time the node process a specific operation (example in figure 2). Such information allows real time observation of the node consumption. This consumption, modeled by appropriate functions (function EngSens in figure 2), can consider different elements: message length, delay of transmission, etc.

Due to the paper limitation, we will not detail subnets associated with the three other node's operations.

HLP-net modelling the behaviour of the sink As previously presented, the sink has two main functions:

- the processing of the received alert messages,
- the periodic broadcast of the control message.

Figure **??** represents the HLP-net modelling the behaviour of the sink. Each function of the sink is modeled by a substitution transition that an associated subnet details its achievement.

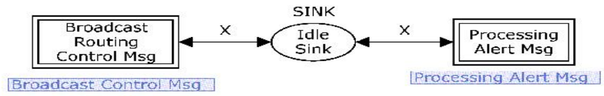

Fig. 3. The HLP-net "Sink"

The processing of the alert messages is represented by the substitution transition *"Processing Alert Msg*. Figure 4 represents the subnet associated with this transition. This transition is fired when (i) a token representing an alert message is placed in *"Received Alert Msgs"* and (ii) the sink is idle (there is a token in the "Idle Sink"). "

Fig. 4. The subnet "Processing Alert Msg"

The place *"Received Alert Msgs"* is merged with the place representing transmitted message in the subnet associated with the substitution transition *"Transmit Alert Msg"*. Such fusion Ratzer et al. (2003) allows the synchronisation of the two subnets. When destination node (modeled by the first element of the token handled by these places) is equal to 0, then current token has reached the sink and enable the transition *"Process Alert Msg"*.

The periodic broadcast of the control messages is modeled by the substitution transition *"Broadcast Routing Control Msg"* (not detailled due to the paper limitations).

4. THE USE OF THE HLP-NET MODEL

Formal modelling the WSN behaviour is not a final objective. Indeed, the HLP-net was developed to allow formal validation of the global WSN properties. Originally, we have developed the HLP-net model to validate the properties of the two previously designed routing and activity scheduling protocols.

At the considered WSN example, the nodes, periodically, self-schedule their activies deciding to remain active to preserve the coverage of the target area as presented in Zairi et al. (2009). After this decision, only active nodes compute the Pareto optimal paths connecting them to the base station according to the protocol of Zairi et al. (2008).

The obtained HLP-net model allows simulation and formal analyses of the WSN behaviour. These two facilities were exploited to validate the WSN behaviour.

4.1 Simulation

During the simulation of the WSN behaviour, the designer can particularly observe the energy spent when achieving the specific operations. A set of monitors can be integrated to the HLP-net model to observe its simulation and produce output files which may be used for drawing curves.

Simulation may be also used to estimate the network lifetime under some assumptions as for example the frequency of the fire detection. Based on these results different protocols (routing, MAC, activity scheduling...) can be compared to prove their efficiency regarding the considered application.

Proposed routing and coverage protocols was already simulated using a specific WSN simulator (PowerTOSSIM [Shnayder et al. (2004)]). The obtained results (concerning the routing paths and the number of inactive nodes) using these two simulators were equivalent. This observation conforts us with the fact that the WSN properties are well conserved in the developed HLP-net. Table 1 presents some examples of the obtained results observing the simulation the developed HLP-net

The primary goal of the developed model is the formal validation of the studied WSN behaviour.

4.2 Formal performance analyses

The proposed HLP-net model allows formal validation of some properties of the studied WSN. This validation may be performed based on the state space of the studied HLP-net which is directly generated by CPN Tools. Formal validation allows the verification of *quantitative* and *qualitative* properties. Such properties may be global, associated with the whole network, or particular, associated with a specific node.

Some qualitative properties that could be verified are:

- the deadlock-free states: A deadlock is a situation wherein two or more components are waiting for the other to finish, and thus neither ever does. We have easily verified that the state spaces of a simple studied WSN does not include deadlock states.
- the connectivity of all working node to the sink using the determined optimal neighbours. According to the algorithm used for the determination of the optimal paths, each node memorises only local information about its one hop optimal neighbours. We have verified, based on a backtracking algorithm, that using locally memorised information (defined by the marking of the place *"Optimal Paths"*) and choosing any destination neighbour, it is possible to reach the base station.
- the arrival order of the control messages does not influence the final results. For final states, representing the end of the determination of optimal paths at a specific round, the marking of the place *"Optimal Paths"* is the same.
- an alert message is transmitted and arrive to the sink any time a fire is detected. From each state enabling the transition *"Fire"*, it is possible to reach a state where the specific token (representing the considered message) is received and processed by the sink (firing the transition *"Process Alert Msg"*).

As quantitative properties, we can check that:

- the number of exchanged control messages for the determination of the optimal paths, for a specific round, is bounded. This information correspond to the firing number of the transition *"Broadcast Cont Msg"*.
- there is no more control messages waiting to be processed. Such propertie can be verified by checking, at a state representing the end of the optimal paths determination, that the marking of the place *"Cont Msg to be processed"* is empty.
- the global connectivity performance (equals to the time when the network, made by the working nodes, is no more connected) is maximum.
- the worst case lifetime which correspond to the shortest network's lifetime observing all the situation.
- the safety propertie (after time T, the network still has more than x% of working nodes) is respected. The rate of working nodes can be calculated for each state where all nodes have made their decisions (number of tokens in the place *"Active Sensors"*).

The use of hierarchical model has major advantages. Indeed, add to the ability to make easier the modelling of the complex system, such alternative allows to independently verify each sub-net properties. Hierarchical modelling allows to have more compact and understanding models. Using each sub-net makes easier the validation of individual component or task. In the same cases, it was not possible to generate the global state spaces representing the global WSN behaviour. It was more accommodate to validate each node function independently considering input information modelling the states of the other functions.

5. CONCLUSION

This paper has presented a HLP-net modelling the global behaviour of a WSN. The proposed model represents the behaviour of each WSN component: the nodes and the sink. The modeled behaviours include: the application, the protocols, an abstraction of the hardware energy consumption model and the environment as viewed by the nodes. The proposed model is symmetrical as the considered WSNs are homogeneous where all the nodes follow the same behaviour.

The obtained model may be simulated to validate the behaviour of a WSN made of hundreds of nodes. In addition, the presented model has different major advantages compared to the existing simulator dedicated to WSN. Indeed, it:

Table 1. Simulation results concerning the scheduling protocol

Algorithm	Number of inactive nodes	Disactivation ratio	Number of sent messages
ERGS	44	59.5	156

i allows the formal validation of the WSNs properties before deployment,

ii is generic. As in most cases the nodes have the same behaviour, it is easy to model this behaviour. The specificity associated with each node will be modeled through the initial marking of the HLP-net.

iii includes different level of abstraction. In the HLP-net, each operation is represented by a transition. When more details about the achievement of a specific operation must be included, the associated transition will be defined as substitution transition. The details will be modeled by the associated subnet.

iiii the used subnet are substitutable. Indeed, different subnets may be associated with the same substitution transition to detail its realisation. The user may choose one of those subnets according to the considered protocol, component or level of abstraction.

Since this system is symmetrical and has a modular structure, we think that combine modular verification Abid and Zouari (2007) and symbolic reachability graphs Chiola et al. (1997) allows to reduce the problem of the state space explosion and reduce the required effort to check the desired properties. The future works will focus on this objective.

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