Towards the Formal Performance Analysis of Wireless Sensor Networks

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***Abstract*—The performance of Wireless Sensor Networks (WSNs) is traditionally analyzed using simulation or paper-and-pencil proof methods. However, such methods cannot ascertain accurate analysis, which is a serious drawback for safety and financial-critical applications. In order to overcome this limitation, we propose to use a higher-order-logic theorem prover (HOL) to formally analyze the performance of WSNs. In particular, this paper presents a generic formal performance analysis methodology for WSNs using the k-set randomized scheduling as an energy saving approach. The proposed methodology is primarily based on the formalized theories of measure and probability. For illustration purposes, we formally analyze the performance of a WSN deployed for volcanic earthquake detection.**

***Keywords*-Wireless Sensor Networks, k-set Randomized Scheduling, Probabilistic Analysis, Formal Verification, Theorem Proving, HOL4.**

I. Introduction

Wireless Sensor Networks are being increasingly used in many safety-critical applications, like natural disasters monitoring, railways, and military [1]. Such networks are basically composed of a collection of battery-powered and wirelessly-connected tiny devices. In this context, extending the network lifetime is very critical [1], and thus randomized nodes scheduling [2] is commonly applied. The main idea here is to make an efficient collaboration between the nodes so that they randomly organize themselves into alternatively working subsets and hence preserving the overall energy consumption of the system.

The un-deterministic and unpredictable nature of random scheduling makes it very challenging to analyze for all possible cases. Traditionally, paper-and-pencil and simulation based probabilistic techniques have been used to analyze the performance of random scheduling for WSNs [3,4]. In such analysis, a mathematical model is built by first identifying the required random variables and the corresponding performance attributes. Then, a rigourous analysis based on the theoretical foundations of probability is done. Simulation, using the Monte Carlo method [5], is finally used to validate the analytical results. Due to the inherent incompleteness of simulation coupled with the rounding errors of computer arithmetics, we cannot term these analysis as 100% reliable, which is a serious limitation for mission-critical WSNs.

Formal methods [6] can overcome the limitations of simulation and have been used to validate a wide range of hardware and software systems. Such methods enhance the analysis reliability using rigorous mathematical techniques to model and verify the given system. Formal methods have also been explored for analyzing WSNs but most of the existing work is focused on analyzing their functional aspects only. However, given the wide application of WSNs in safety and financial-critical domains, there is a dire need to accurately assess their performance as well. The current paper is mainly focused on fulfilling this requirement.

We propose to use a higher-order-logic theorem prover (HOL) [7] for the formal performance analysis of any WSN using the k-set randomized scheduling [3] as an energy saving approach. The main motivation behind using higher-order logic is its high expressiveness that can be leveraged to model any system including its random and unpredictable components using appropriate random variables [8,9]. The proposed methodology is primarily based on the formalized theoretical foundations of the k-set randomized scheduling and the most relevant performance properties including coverage, detection and lifetime [2]. This paper provides a detailed description of the different steps and requirements to conduct the formal performance analysis of any randomly-scheduled WSNs. The practical effectiveness of the proposed methodology is illustrated by presenting the formal performance analysis of a WSN deployed for volcanic earthquake detection. Thanks to the proposed approach, this is the first time, to the best of our knowledge, that the performance analysis of this kind of a WSN application is analyzed in a complete formal manner.

The rest of the paper is organized as follows. We first survey some related work in Section II. Then, we briefly present, in Section III, the k-set randomized scheduling for WSNs. In Section IV, we describe in detail the proposed methodology for the formal performance analysis of WSNs. Section V presents some of the already developed formalization, including the k-set randomized scheduling and the coverage property. Section VI presents the illustrative application for the volcanic earthquake detection. We finally conclude the paper in Section VII.

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II. Related Work

In [3,4], a coverage-based random scheduling algorithm has been analyzed using a mathematical model. Then, evaluations have been done using a Java simulator by setting the monitored region to 200m$\times$200m, the detection range to 10m, and the number of subsets to 6. These simulations are done using the Monte Carlo method [5]. This widely used validation method is based on approximately answering a query on a probability distribution by analyzing a large number of samples. Statistical quantities, such as expectation and variance, may then be calculated, based on the data collected during the sampling process, using their mathematical relations in a computer. Due to the inherent nature of simulation coupled with the usage of computer arithmetic, these probabilistic analysis results cannot be termed as 100% accurate. Moreover, the analysis results are not generic, i.e., they are specific to a region, range and number of subsets.

Formal verification has also been used for analyzing Wireless Sensor Networks. In [10], the state-based formal verification method, model checking [11], is used to verify WSNs security aspects in the SLEDE framework. The effectiveness of this framework has been shown by verifying two commonly used security protocols and some known security flaws have been detected. Similarly, a model checking based framework, called NesC@PAT [12], is also used for verifying WSNs implementations in NesC. However, in both of these works, the size of the state-based model increases exponentially as the complexity of the given WSN grows leading to the well-known state-space explosion problem. For example, in [12], it is reported that over 1 million states are generated in order to verify a single property. In addition, the two mentioned works do not allow capturing randomness of WSNs into account, which is a strict limitation since most of the WSN algorithms are probabilistic.

Besides model checking, HOL theorem proving [7] has also been used for analyzing WSN algorithms. In [13], a WSN algorithm is formally modelled, within the PVS system, by utilizing a library of mathematically specified sub-blocks, like nodes, network structure, communication primitives and protocols. Furthermore, the resulting framework is enriched by some theories expressing probabilistic scenarios like nodes mobility and link quality changes. The feasibility of this framework is illustrated by manually analyzing the trace execution of the Surge algorithm [14], and formally verifying the correctness of the message delivery for the Reverse Path Forwarding algorithm [13]. Nevertheless, the randomness here is modeled by using a pseudo-random generator, which compromises the accuracy of the analysis.

In [15], the probabilistic analysis foundations developed in the HOL theorem prover [8,9] have been used to formally verify some performance characteristics of the k-set randomized algorithm. The results in [15] have been found to be absolutely accurate since a measure theoretic probability theory is used to analyze the WSN algorithm within the sound core of a theorem prover. However, the scope of this work is limited to performance related to coverage aspects only. Whereas, there are many other widely used performance metrics, such as detection probability, detection delay and lifetime. In the current paper, we extend the ideas presented in [15] to cater for the formal verification of these missing performance characteristics.

III. The k-set Randomized Scheduling Algorithm for WSNs

Consider a WSN that is formed by randomly deploying n nodes over a field of interest. Every sensor in this WSN can only sense the environment and detect events within its sensing range r. During the initialization phase, the k-set randomized scheduling [3] is run on every node as follows. Each node starts by randomly picking a number ranging from 0 to $(k-1)$. We denote the selected number by i. Now, the node is assigned to the sub-network S_i and will be turned on only during the working time slot T_i of that subset. During the other time slots, it will be in the idle state. Hence, during the time slot T_i, only the nodes belonging to the sub-network S_i will be active and can detect an occurring event. The scheduling algorithm terminates by creating k disjoint sub-networks that work independently and alternatively so that the energy over the whole network can be preserved. It is important to note that each node joins a single subset with the same probability $1/k$ since nodes are uniformly and independently deployed over the area.

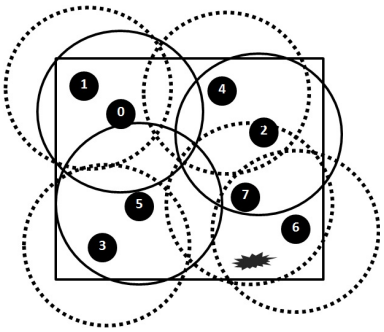

Figure 1. An Example of the k-set Randomized Scheduling for 8 Nodes.

Fig. 1 shows how the k-set randomized scheduling algorithm splits arbitrarily a WSN of eight randomly-deployed nodes to two subsets. Each node randomly chooses between 0 or 1 in order to be assigned to one of the two subsets, i.e., S_0 or S_1. Suppose that nodes 0; 2; 5 select the number 0 and join the subset S_0 and nodes 1; 3; 4; 6; 7; choose the number 1 and join the subset S_1. These two sub-networks will work alternatively, i.e., when nodes 0; 2; 5, with sensing ranges denoted by the solid circles, are active, nodes 1; 3; 4; 6; 7, illustrated by the dashed circles, will be idle and vice-versa.

IV. Performance Analysis Methodology

The k-set randomized scheduling, as previously described, is very effective in prolonging the network lifetime of randomly-deployed WSNs by organizing the nodes into subsets that work alternatively. Thus, the lifetime of a WSN is one of its most interesting performance aspect. The network lifetime, denoted by T_{Nlife}, is defined as follows [16]:

$$T_{Nlife} = k \times T_{Slife} \tag{1}$$

where T_{Slife} is the average lifetime of a typical sensor and k represents the number of sub-networks.

According to Equation (1), in order to maximize the network lifetime T_{Nlife}, we have to maximize the number of sub-networks k. Based on the theoretical analysis done in [16], other performance attributes such as the detection delay D, the detection probability P_d, and the network coverage intensity C_n, also depend on the values of k. For example, a very large k will imply an infinite detection delay D and a worse coverage C_n, which is not desired. Consequently, the maximization on the values of k has to be done accurately while taking into account the bounds of the main QoS constraints. Thereby, there is an upper bound on the values of k so that a good coverage can be ensured with an acceptable delay D. The lifetime maximization is viewed hence as an optimization problem under Quality of Service (QoS) constraints and is defined as [16]:

$$\begin{cases} 1.\ D \leq QoS_{DD} \\ 2.\ P_d \geq QoS_{DP} \\ 3.\ C_n \geq QoS_{C_n} \\ 4.\ n = c. \end{cases} \tag{2}$$

where QoS_{DD}, QoS_{DP}, and QoS_{C_n} are predefined QoS constraints associated to the delay D, the detection probability P_d, and the network coverage intensity C_n, respectively, n is the number of nodes, and c is a constant value. These QoS constraints mainly depend on specific application requirements for which the WSN is designed.

The main objective of our work is to develop the foundational formalization to formally verify the key performance attributes of any WSN using the k-set randomized scheduling as an energy saving approach. For that purpose, the higher-order-logic formalizations of the the network coverage C_n, detection delay D and detection probability P_d, are required to be developed first. Based on these formalization, we can then formally verify the optimal lifetime solution for the above optimization problem, as formulated in (2). Fig. 2 depicts the basic building blocks of the proposed methodology while the formalization requirements are represented by the dark grey shaded boxes. The proposed formal performance analysis methodology can be summarized as follows:

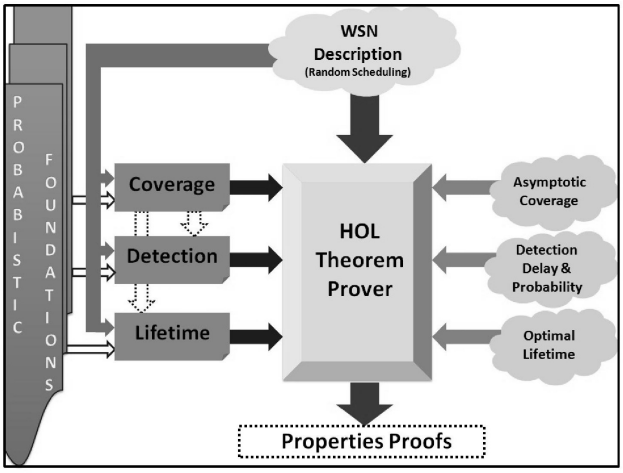

Figure 2. Formal Performance Analysis Methodology

1) Formalization of the k-set randomized scheduling algorithm using the HOL definition of the Uniform random variable [9].
2) Formalization of the coverage attribute and the formal verification of some of its key properties, including some asymptotic results, using the existing HOL formalizations of expectation [8].
3) Formalization of the detection aspect including the detection probability of an intrusion, the average delay spent for a detection and its limiting behavior.
4) Formal specification of the lifetime property as described in Equation (1).
5) Formal verification of the optimal lifetime properties (2) in HOL under QoS requirements depending on coverage and detection. Here, we mainly require the coverage and detection theories along with the corresponding asymptotic analysis developed in the previous steps.

It is worthy to note that the formalizations steps, mentioned above, are mainly based on the paper-and-pencil probabilistic analysis of the k-set randomized algorithm available in the open literature [3,16]. Whereas, our main contribution is to formalize them in higher-order-logic to facilitate the formal performance analysis of WSNs within the sound core of the HOL theorem prover.

Due to the wide applicability of the k-set randomized algorithm to prolong the lifetime of randomly-deployed WSNs, the proposed methodology can be used for analyzing the performance of various real-world applications, such as, environmental outdoor monitoring [17] or enemy intrusion detection.

In summary, we believe that the proposed methodology for the formal performance analysis of WSNs is distin-

guishable from previous works done by simulation or model checking in several aspects. Indeed, it

- allows the formal performance analysis of a variety of critical aspects associated with the k-set randomized scheduling, due to its modularity,
- provides the verification of generic, universally quantified, theorems,
- ensures accurate results due to the mathematical nature of the models and the soundness of theorem proving,
- facilitates analyzing a wide range of real-world WSN applications.

V. Foundational HOL Formalizations

In this section, we present the HOL formalization related to the first two steps of the proposed methodology, depicted in Fig.2.

A. Formalization of the k-set Randomized Scheduling

The main idea of the randomized scheduling of nodes, as described in Section III, is to randomly assign a sub-network, out of the k available options, to each node. This assignment is done uniformly in order to have a fair distribution of nodes. We modeled this behavior in higher-order logic as follows:

Definition 1.

```
⊢ (∀ k. rd_subsets 0 k = []) ∧
  (∀ c,k. rd_subsets (c+1) k =
  (prob_uniform k)::(rd_subsets c k)).
```

The function `rd_subsets` generates a list of Uniform random variables, and accepts two parameters: c, the number of sensors that covers a specific point inside the field, and k, the number of sub-networks. In this definition, we use the predefined HOL function `prob_uniform` [9] which takes as input a natural number k and generates a Uniform (k) random variable.

B. The Coverage Theory

Since the assignment of the sensor nodes to the k sub-networks is randomly done, it may happen that some of the sub-networks are empty. Moreover, due to the random deployment of nodes, the random scheduling can lead to a situation where certain parts of the area are not monitored at all or simultaneously monitored by many sensors. While analyzing nodes scheduling schemes, we are usually interested in finding the probability that an occurring event can be detected at each point of the region by at least one active sensor. Each point of the area is hence characterized by a coverage intensity C_p, which is defined as the average time during which the point is covered in a scheduling cycle [3].

$$C_p = \frac{E[X] \times T}{k \times T} \tag{3}$$

where $E[X]$ denotes the expectation of the random variable X describing the total number of non-empty subsets, i.e.

$$X = \sum_{j=0}^{k-1} X_j \tag{4}$$

where X_j is the Bernoulli random variable which value is 1 in case of a non-empty subset.

The coverage intensity of a WSN using the k-set randomized scheduling can be formalized in higher-order logic as a function `cvrge_intsty_pt` [15] that accepts two parameters, i.e., the number of sub-networks k and the number of nodes c covering a specific point inside a field. It utilizes the formalized Uniform and Bernoulli random variables to return the coverage intensity of a point using Equations (1) and (2).

Based on this formalization, we formally verified the following mathematical expression for the coverage intensity of a point.

Theorem 1.

```
⊢ ∀ c,k. cvrge_intsty_pt c k =
         1 − (1 − (1/(k+1)))^c.
```

where the variable c above is a Binomial random variable with success probability q, i.e., the probability that a sensor covers a given point. Using this fact, the coverage intensity of the whole WSN with n nodes can be formally defined as:

Definition 2.

```
⊢ ∀ q,n,k. cvrge_intsty_network q n k =
    expec_fn (λx. 1 + −1×(1 − 1/(k+1))^x)
    (prob_binomial_p n q).
```

The HOL function `prob_binomial` represents the Binomial random variable with n trials and success probability q [9] and the function `expec_fn` represents the expectation of a function of a random variable [9]. While the functions of type $(\lambda x.\, C\, x)$ represent the lambda abstraction functions in HOL that accept a parameter x and return Cx.

We also verified the following alternate mathematical expression for `cvrge_intsty_network`.

Theorem 2.

```
⊢ ∀ n,q,k. (0 ≤ q) ∧ (q ≤ 1) ∧ (1 ≤ n)
⇒ (cvrge_intsty_network q n k =
   (1 − (1−(q/(k+1)))^n)).
```

The assumptions of the above theorem ensure that the probability q lies in the interval [0,1] and the number of nodes is at least 1.

The formalization and verification details of the definitions and theorems, presented in this section, are available in [15]. It is important to note that this was a very tedious effort, consuming 200 man hours and 1500 lines of code, mainly due to the un-decidable nature of higher-order logic. However, these results greatly facilitate the formal analysis of real-world WSNs as will be illustrated in the next section.

VI. Formal Analysis of WSN for Volcanic Earthquake Detection

In this section, we are interested in formally analyzing the coverage performance of a WSN for volcanic earthquake monitoring inside the crater of Mount St. Helens in northwestern U.S [18]. Indeed, due to the safety-critical feature of the target application and the harsh nature of the field of interest, it is very important that the deployed WSN remains alive as long as possible while ensuring a good coverage. The k-set randomized scheduling algorithm is thus applied to preserve energy. Hence, the deployed nodes, based on iMote2 sensors [18], are airdropped into the crater of the Mount over a radial distance of $100m$ from the vent [18]. The total size of the area is thus a = $31400m^2$ while the sensors have a sensing range r = $40m$.

We can formally specify the given volcanic earthquake application by specializing Definition 1 since it describes the generic coverage intensity of a WSN. In the specified application, the success probability q of a sensor covering a point is given by the ratio of the radius covered by a sensor with the total area, i.e., q = r/a = 0.127×10^{-2}. Thus, the coverage network intensity of the given volcanic earthquake monitoring application can be formalized as follows:

Definition 3.

```
⊢ cvrge_intsty_volc_WSN n k =
    cvrge_intsty_network 0.127×10^-2 n k.
```

The above definition accepts two parameters, i.e., the total number of sensor nodes n and the number subsets k. It returns the coverage intensity of the system as the average value using Definition 1.

The next step in the probabilistic analysis using the theorem proving approach is to specify the properties of interest as higher-order-logic proof goals and verify them in a theorem prover. For our given volcanic earthquake detection application, we verify the following theorem related to its coverage intensity by using Theorems 1 and 2.

Theorem 3.

```
⊢ ∀ n,k. (1 ≤ n) ⇒
   (cvrge_intsty_volc_WSN n k =
   (1 - (k+0.873×10^-2/(k+1))^n)).
```

Based on the formal verification done in Theorem 3, we now conduct a formal asymptotic analysis of the probabilistic coverage based on WSN parameters n and k. Hence, we formally verify, in Theorem 4, that the network coverage intensity C_n is an increasing function of n.

Theorem 4.

```
⊢ ∀ n,k. (0 < k) ⇒
 (mono (λn. cvrge_intsty_volc_WSN n k)).
```

where `mono` is the HOL function specifying a monotone function. Theorem 4 can be used to deduce useful results for the given application. For example, we can deduce that under the randomized scheduling, which divides the network into a given number k of sub-networks, any network coverage intensity C_n can be achieved by increasing the number of deployed nodes n.

Besides, we formally verify in Theorem 5 that when n is very large, C_n tends to its ideal value 1.

Theorem 5.

```
⊢ ∀ n,k. (0 < k) ∧ (1 ≤ n) ⇒
((λn. cvrge_intsty_volc_WSN n k) --> 1).
```

where ((λn. f n) → c) indicates that the sequence f tends to the value c when n is very large.

After the nodes deployment, the number of nodes becomes known and fixed. Enhancing the coverage performance of the network by increasing the number of nodes n, as stated in Theorem 4, may not be usually feasible. Indeed, a second deployment can be very costly in the context of inhospitable fields, where nodes are usually airdropped. Contrarily, in the case of the WSN deployed for volcanic earthquake detection using the k-set randomized scheduling, it is possible to increase the coverage by adjusting the number of disjoint subsets *k* by a suitable value. We can formally deduce that for a given *n* and a network coverage intensity of at least *t*, the upper bound on the number of disjoint subsets *k* is given as follows:

Theorem 6.

```
⊢ ∀ n,k. (1 ≤ n) ∧ (0 < k) ∧ (t ≤
cvrge_intsty_volc_WSN n k)
```

$$\Rightarrow\ k \leq \frac{0.127 \times 10^{-2}}{1 - e^{\frac{\ln(1-t)}{n}}}.$$

From the above theorem, we notice an interesting dependency between the number of sub-networks k and the required coverage. It is hence very interesting to study the limiting behavior of the network coverage intensity C_n based on the parameter k. For this purpose, we have been able to formally verify, in Theorem 7, that C_n decreases with an increase in the value of k.

Theorem 7.

```
⊢ ∀ n,k. (0 < k) ∧ (1 ≤ n) ⇒
(mono (λk. cvrge_intsty_volc_WSN n k)).
```

Consequently, for the volcanic earthquake monitoring application, increasing k surely saves more energy, a significant increase in k may lead to several sub-networks, which in turns translates to a poor network coverage intensity C_n. Hence, we formally confirm, in Theorem 8, that given a number of nodes n, the network coverage intensity C_n goes to 0 when k becomes very large.

Theorem 8.

```
⊢ ∀ n,k. (0 < k) ∧ (1 ≤ n) ⇒
((λk. cvrge_intsty_volc_WSN n k) --> 0).
```

The analysis described above consumed only 150 lines of HOL code and thus clearly indicates the effectiveness of the formal development, presented in Section V. Unlike the unreliable results from classical analysis techniques, like paper-and-pencil based analysis or simulation, our results for this WSN for volcanic earthquake detection are guaranteed to be accurate. This distinguishing feature is due to the inherent soundness of theorem proving and its generic nature, e.g., the coverage intensity for any given values of n and k can be computed by instantiating Theorem 3 with appropriate values. In addition, the formal verification of the limiting behavior of C_n allows accurate asymptotic reasoning of the deployed WSN. Finally, for each of the formally verified theorems, the set of required assumptions is clearly stated so there is no doubt about missing a critical assumption. This feature is not available in classical analysis techniques where many assumptions can be implicitly taken into account without explicitly mentioning them.

VII. Conclusion

This paper presents a methodology for formally analyzing the performance of Wireless Sensor Networks that use the k-set randomized scheduling algorithm to preserve energy. The main idea of the proposed methodology is to formally model the given WSN using appropriate random variables functions and then reason about its coverage, detection and lifetime properties in the sound core of the HOL theorem prover. The paper also presents a formal generic model of a WSN using the k-set randomized scheduling algorithm and the verification of some widely used coverage aspects. The usefulness of the proposed approach has been already shown by verifying the scheduling performance of a real-world WSN for forest fire detection [19]. In this paper, we provided, for the first time, a reliable probabilistic analysis of the design of a WSN for volcanic earthquake detection.

We are currently working on extending the formal reasoning support for detection and lifetime aspects as well. This way, the performance of other interesting case studies, such as underwater monitoring can also be formally analyzed.

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