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The Logic Sense Request of WSN and Its Analysis Model

Zhengyi Tang[1,3], Xingsi Xue[1,3], Jinshui Wang[1,3]
[1]College of Information Science and Engineering
[3]Fujian Provincial Key Laboratory of Big Data Mining and Applications
Fujian University of Technology
No.3 South Xuefu Road, University Town, Fuzhou, Fujian, 350118, China
tangzy84@126.com, jack8375@gmail.com, wangjinshui@gmail.com

Zhi Hang[2,4,*]
[2]Key Laboratory of Hunan Province for New Retail Virtual Reality Technology
[4]Institute of Big Data and Internet Innovation
Hunan University of Commerce
No.569 Yuelu Road, Changsha, Hunan, 410205, China
*Corresponding author: william_falcon@126.com

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Abstract. *This paper researched the sensor scheduling strategy of WSN, and its influence on the sensed sequence for environment objects. For reflecting this influence, it proposed a new type of sense request based on logic constraint for WSN, namely logic sense request. Then it gave a formal model which can analyze the logic sense request. This formal model uses transition system of sense pattern to specify the sensor scheduling strategy of WSN, and the logic sense request is specified by temporal logic of sense. Whether a sensor scheduling strategy can meet a logic sense request is translated into a mathematical proof: Whether is a temporal logic of sense formula true in a transition system of sense pattern. By some cases of inference verification, it showed this analysis model is feasible.*
Keywords: Wireless Sensor Network, Sense Request, Transition System, Temporal Logic, Formal Method

1. **Introduction.** The wireless sensor network, namely WSN, is an ad-hoc network which is consisted of many low-budget sensors which have low power consumption[1]. The sensors have the ability of sense, data processing and storage, wireless communication. All sensors sense, process and transmit the information of objects in the coverage of WSN by cooperation. The appearance of WSN changes the interactive mode between human and physical world, and the physical world combine with informational world becoming possible[2].

The WSN is a data-centric network, and an important measure of quality is the ability of acquiring environmental information[3]. This measure is the prime consideration of designing WSN also. At present, the coverage of WSN, namely the physical region whose information can be acquired by WSN, is the main perspective for researching the information acquisition capability of WSN[4]. The researchers research different types of coverage problem from the perspective of sensor deployment and sensor model[5, 6, 7, 8], and the purpose is finding the optimal strategy for sensor deployment, namely the coverage of

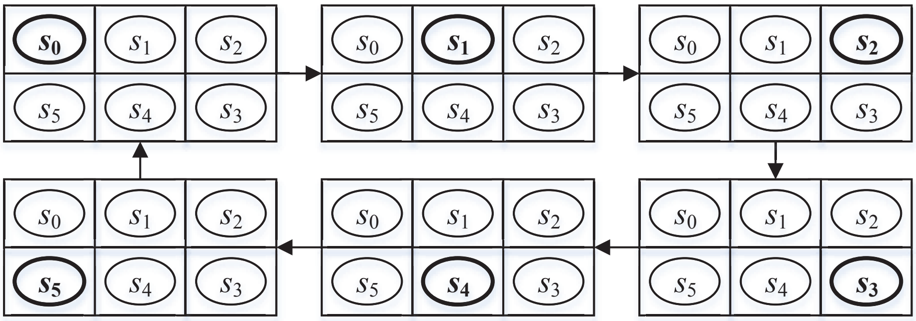

FIGURE 1. Polling scheduling strategy

WSN is as large as possible and the energy consumption and the sensor number of WSN is as small as possible[9].

However, the research for the coverage of WSN didnt involve the influence of sensor scheduling strategy. Because of this influence, the WSN which satisfy the coverage request may not acquire the data with logic constraint. This paper focused on the sense scheduling strategy of WSN and its influence on the sensed sequence for environment objects. It proposed the logic sense request by adding the temporal logic constraint to the sense relation between the sensors and environment objects. This idea expands the research scope of sense ability of WSN. For analyzing the logic sense request, it gave an analysis model by formal method. This analysis model consists of two new formal language: transition system of sense pattern and temporal logic of sense, one is used to specify the running trajectory of sensors and another one is used to specify the sense request with temporal logic constraint. This model is a feasible method for verifying the logic sense request of WSN.

2. **The Sensor Scheduling Strategy of WSN and Its Logic Sense Request.** For saving energy, the sensors of WSN do not always work generally. The WSN adjusts the working state of sensors to acquire and transmit environment data intermittently or periodically[10]. This process is called sensor scheduling strategy. By the influence of sensor scheduling strategy, multiple WSNs with same quantity, standard and deployment strategy of sensors may be different in the ability of sense. The formal definition of sensor scheduling strategy is given in the following definition:

Definition 2.1. *(Sensor Scheduling Strategy) A sensor scheduling strategy is a triple SCH = (W, C, T), where:*

(1) $W = \{w_1, w_2, w_n\}$ *is the set of sensor states, and the* w_i *is the state of the i-th sensor.*

(2) $C = \{c_1, c_2, c_m\} \cup \{\oslash\}$ *is the set of control conditions, and* $\oslash \in C$ *means that the control condition can be empty.*

(3) $T \subseteq W \times C \times W$ *is the set of state transition rules. A state transition rule is an ordered pair* $t =< w, c, w' >$*, it means that the sensor state will change from* w *to* w' *when the control condition* c *is satisfied.*

Assuming there is a WSN with six sensors, and the coverage is six connected zones. The deployment strategy is every zone have one sensor. The sensor acquires the temperature of the zone. Considering the sensor scheduling strategy in figure 1, it activates only one sensor in one time cycle, namely polling. The active sensor acquires and transmits the temperature information of its deployment zone. In figure 1, the bold node means the active sensor.

This scheduling strategy can satisfy the request of observation, such as the variation of zones temperature. But it cant satisfy the sense request which need the real-time data of multiple zones. For example, when the temperature of a zone is abnormally high, it is need to find out the cause. One possible cause is that there is exceptional heat source in the abnormal zone. But the exceptional heat source also may be in the neighboring zones, and it needs the temperatures of neighboring zones to confirm. The cause cant be confirmed by polling strategy, because this strategy cant acquire enough information. This type of sense request can be described as a set of logic constraints for sensor state:

(1) When sensor s_0 senses the environment object, s_1 and s_5 must also sense environment objects.

(2) When sensor s_1 senses the environment object, s_0, s_2 and s_4 must also sense environment objects.

(3) When sensor s_2 senses the environment object, s_1 and s_3 must also sense environment objects.

(4) When sensor s_3 senses the environment object, s_2 and s_4 must also sense environment objects.

(5) When sensor s_4 senses the environment object, s_1, s_3 and s_5 must also sense environment objects.

(6) When sensor s_5 senses the environment object, s_0 and s_4 must also sense environment objects.

These sense requests which contain logic constraint are called logic sense request. It is easy to judge that the sensor scheduling strategy in figure 1 cant satisfy the above sense request by manual analysis. But when the sensors and environments are plentiful, and the sense relation between them are complex, it is very hard to judge whether a logic sense request can be satisfied by manual analysis. So, it needs a systematic and exact approach for analysis and verification.

3. The Analysis Model for Logic Sense Request.

3.1. The Formal Analysis Model. The formal method is an effective technology for analyzing whether a system satisfies the predicted property. It uses mathematic method to specify system and property. On this basis, it gives corresponding algorithm to verify whether these two models are consistent automatically[11]. The formal method provides a verification framework, and the developer can specify, develop and verify system in this framework systematically.

A formal analysis model can be specified as the following form: $M \models F$

The M is a formal specification of system, and the F is the formal specification of predicted system property. They are gained all by mathematic method. These two processes are called formal specification. It can also use mathematic method to verify whether F is satisfied by M. This process is called formal verification. The formal method can describe the action and feature of system succinctly and accurately, and it can also give the strict proof for the satisfiability of predicted system property. By the automatic tool of mathematic proof and deduction, the formal method may be highly automatic.

To construct the formal analysis model of WSNs logic sense request, there are two formal specifications:

(1) The sensor scheduling strategy must be specified as a system model M.

(2) The logic sense request must be specified as a predicted property F.

According to the formal definition of sensor scheduling strategy, the scheduling strategy reflects the change of sensor state. It can be specified by finite state transition system named transition system of sense pattern. The logic sense request reflects the sensed situation of environment object. Because the sensed situation is variable, it is suitable to be specified by temporal logic named temporal logic of sense.

There is another benefit of using the above specifications: the formal method which is made up of these specifications has the same structure with model checking technology. Because the automatic degree of model checking is very high, the above specifications can also be verified automatically in theory.

3.2. **The Formal Analysis Model.** The transition system of sense pattern, namely TSSP is the tool of modeling the running trajectory of WSN, and it is a finite state transition system. It relates the environment element to the sensor, and the sensed situation of environment object is expressed by the sensor state. By such process, the sensor scheduling strategy of WSN can be specified by TSSP.

The definition of the TSSP is following:

Definition 3.1. *(Transition System of Sense Pattern) A transition system of sense pattern $M = (N, V, R, S, L, D)$, where:*

(1) $N = \{n_i | n_i \in \{active, inactive\}, 0 \le i < k\}$

(2) $V = \{v_i | 0 \le i < m\}$

(3) $R = \{< n_i, v_j > | n_i \in N, v_j \in V\}$

(4) $S = \{< n_0, n_1, n_{k-1} > | n_i \in N\}$

(5) $L = \{n \leftarrow x | n \in N, x \in \{active, inactive\}\}$

(6) $D \subseteq S \times L \times S$

The meaning of the symbols are following:

(1) N is the set of sensor elements, and the value range is $\{active, inactive\}$. The two values represent the sensor is working or dormant orderly.

(2) V is the set of environment elements, it means the environment objects which are sensed by WSN.

(3) R is the sense relation which describes the corresponding relation between the sensors and environment elements.

(4) S is the set of sense patterns. A sense patter is a sequence of the sensors states.

(5) L is the set of transition labels, it is the specification of sensor schedule.

(6) D is a set of directed edges. A directed edge is the transition between the sense patterns and satisfies:

$$\forall < s, l, s' > \in D : s'(n) = \begin{cases} x & n \leftarrow x \in l \\ s(n) & else \end{cases}$$

$s(n)$ is the value of sensor n in sense pattern s.

The TSSP specification of sensor scheduling strategy in figure 1 is following:

$M = (N, V, R, S, L, D)$

$N = \{n_0, n_1, n_2, n_3, n_4, n_5\}$

$V = \{v_0, v_1, v_2, v_3, v_4, v_5\}$

$R = \{< n_0, v_0 >, < n_1, v_1 >, < n_2, v_2 >, < n_3, v_3 >, < n_4, v_4 >, < n_5, v_5 >\}$

$S = \{s_0 =< active, inactive, inactive, inactive, inactive, inactive >,$
$s_1 =< inactive, active, inactive, inactive, inactive, inactive >,$
$s_2 =< inactive, inactive, active, inactive, inactive, inactive >,$
$s_3 =< inactive, inactive, inactive, active, inactive, inactive >,$
$s_4 =< inactive, inactive, inactive, inactive, active, inactive >,$
$s_5 =< inactive, inactive, inactive, inactive, inactive, active >\}$

$L = \{l_0 = \{n_0 \leftarrow inactive, n_1 \leftarrow active\},$
$l_1 = \{n_1 \leftarrow inactive, n_2 \leftarrow active\},$

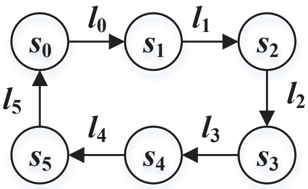

FIGURE 2. The graphical presentation of transition system of sense pattern

$l_2 = \{n_2 \leftarrow inactive, n_3 \leftarrow active\}$,
$l_3 = \{n_3 \leftarrow inactive, n_4 \leftarrow active\}$,
$l_4 = \{n_4 \leftarrow inactive, n_5 \leftarrow active\}$,
$l_5 = \{n_5 \leftarrow inactive, n_0 \leftarrow active\}\}$
$D = \{(s_0, l_0, s_1), (s_1, l_1, s_2), (s_2, l_2, s_3), (s_3, l_3, s_4), (s_4, l_4, s_5), (s_5, l_5, s_0)\}$
The graphical presentation is showed in figure 2.

3.3. **The Temporal Logic of Sense.** Logic formula is a common technology of specifying system property in formal method. The temporal logic is a branch of modal logic, and its model is consists of multiple states. Differing from the propositional logic and predicate logic, the truth value of temporal logic is not fixed in the given model (interpretation), and it may change with the transition of the model states[12]. According to the existence of branch in state transition path, the temporal logic can be divided into two types: linear temporal logic and branching temporal logic. Because the description ability of branching temporal logic is stronger[13], the temporal logic of sense, namely TLS, base on it. Examples for writing definition, lemma, theorem, corollary, example, remark.

The definition 3.2 $\sim$ 3.6 give the syntax of temporal logic of sense:

Definition 3.2. *(Sense Predicate) The sense predicate is sense*(v)*, where* $v \in V$*. It means that whether the environment element* v *is sensed by sensor.*

The sense predicate is the atomic formula of TLS.

Definition 3.3. *(Connective) The connectives of TLS are:* $\neg$, $\vee$, $\wedge$, $\rightarrow$, $\leftrightarrow$.

Definition 3.4. *(Temporal Operator) The temporal logic of TLS are:* $\Box(all)$, $\Diamond(exist)$, $\circ(next)$, $\triangleright(until)$.

Definition 3.5. *(Path Quantifier) The path quantifier of TLS are: A(all), E(exist).*

Definition 3.6. *(Well-Formed Formula) The well-formed formula of TLS is defined as follow:*

(1) The sense predicate is well-formed formula.

(2) If F_1 *and* F_2 *are well-formed formula, then* $\neg F_1, F_1 \vee F_2, F_1 \wedge F_2, F_1 \rightarrow F_2, F_1 \leftrightarrow F_2$ *are also well-formed formula.*

(3) If F_1 *and* F_2 *are well-formed formula, then* $\Box F_1, \Diamond F_1, \circ F_1, F1 \triangleright F_2$ *are also well-formed formula.*

(4) If F *is well-formed formula, then* AF, EF *are also well-formed formula.*

(5) A symbol string is well-formed formula iff it is generated by using the above rules finitely.

In the transition system of sense pattern, it can give the interpretation of TLS formula. In the following definition, F, F_1, F_2 are all well-formed formula.

Definition 3.7. *(Truth Value of Sense Predicate) The truth value of sense predicate relate to sense pattern. In a sense pattern* s*, there are two types of the truth value of sense predicate:*

(1) One element sense: $sense(v) = true$ *iff* $\exists < n, v >\in R : s(n) = active$.

(2) Multiple elements sense: $sense(v) = true$ *iff* $\exists < n, v >\in R \wedge \forall < n, v >\in R : s(n) = active$.

If the truth value of $sense(v)$ in the sense pattern s of TSSP M is $true$, it can be denoted as $(M, s) \models sense(v)$. It can also be simply denoted as $s \models sense(v)$ if there is no confusion.

In one element sense model, an environment element only need to be sensed by one sensor. And in multiple elements sense model, an environment elements need to be sensed by multiple sensors.

Definition 3.8. *(Sematic of Connective) The truth value of a well-formed formula which includes connective only relate to sense pattern. For a sense pattern s:*

(1) $s \models \neg F_1 : s \not\models F_1$

(2) $s \models F_1 \vee F_2 : s \models F_1 \vee s \models F_2$

(3) $s \models F_1 \wedge F_2 : s \models F_1 \wedge s \models F_2$

(4) $s \models F_1 \rightarrow F_2 : s \models F_1 \rightarrow s \models F_2$

(5) $s \models F_1 \leftrightarrow F_2 : s \models F_1 \leftrightarrow s \models F_2$

The connective is used to specify the logic constraint in the sensed situation of environment object. The examples are following:

(1) The temperature and humidity must be sensed at same time.

(2) The temperature or light intensity can be sensed.

(3) When the noise intensity of zone A is sensed, the noise intensity of zone B is also sensed.

The truth value of well-formed formula with temporal operator relate to the transition path of sense pattern:

Definition 3.9. *(Transition Path of Sense Pattern) The transition path of sense pattern is a sequence:* $p =< s_0, l_0, s_1, l_1, s_2, >, s_i \in S, l_i \in L$. *The sense pattern and transition label appear in the path alternately.*

The i-th sense pattern of transition path p is denoted as p_i^s, the i-th transition label is denoted as p_i^l. The set of transition paths of sense pattern is denoted as P.

Definition 3.10. *(Semantic of Temporal Operator) The truth value of a well-formed formula with temporal operator is decided by a transition path. For a transition path of sense pattern* $p =< s_0, l_0, s_1, l_1, s_2, >$:

(1) $p \models \Box F$ *iff* $\forall i \geq 0 : s_i \models F$

(2) $p \models \Diamond F$ *iff* $\exists i \geq 0 : s_i \models F$

(3) $p \models \circ F$ *iff* $s_1 \models F$

(4) $p \models F_1 \rhd F_2$ *iff* $(\forall i \geq 0 : s_i \models F_1) \vee (\exists j \geq 0 : s_j \models F_2 \wedge \forall i < j : s_i \models F_1)$

The temporal operator is used to specified the constraint for change of sensed situation of environment object. For example:

(1) The noise intensity must be sensed at all time.

(2) The humidity must be sensed at next moment.

(3) The temperature of zone A must be sensed at all time before the temperature of zone B can be sensed.

Definition 3.11. *(Semantic of Path Quantifier) If a well-formed formula includes path quantifier, its truth value relate to multiple transition path of sense pattern. For a set of transition path of sense pattern P:*

(1) $P \models AF$ *iff* $\forall p \in P : p \models F$

(2) $P \models EF$ *iff* $\exists p \in P : p \models F$

The path quantifier is used to specify the change of sensed situation can be various. For example:

(1)The temperature must be sensed at all time in any sensed situation.

(2)The temperature can be sensed in any sensed situation.

The set of transition paths of sense pattern in TSSP M is denoted as $M.P$, and $M.P \models F$ can be denoted as $M \models F$.

The operator precedence of TLS is given in table 1:

Table 1. Operator Precedence

Operator	Precedence
$\neg$	1
$\vee, \wedge$	2
$\rightarrow, \leftrightarrow$	3
$\Box, \Diamond, \circ$	4
$\triangleright$	5
A, E	6

3.4. **Safety and Liveness.** The safety and liveness are basic properties of system[14, 15]. The safety means some bad things will never happen in the running of system, and the liveness means some good things will eventually happen in the running of system.

The safety and liveness of WSN can be given from the perspective of environment element:

(1) Continually sense: In some case, the environment element v can be sensed continually, denoted as $E\Box\ sense(v)$.

(2) Always sense: In any case, the environment element v can be sensed at all time, denotes as $A\Box\ sense(v)$.

(3) Ever sense: In some case, the environment element v can be sensed, denoted as $E\Diamond\ sense(v)$.

(4) Always ever sense: In any case, the environment element v can be sensed, denoted as $A\Diamond\ sense(v)$.

4. **The Cases of Inference Verification.** The TLS formulas for the sense requests which are given in the section 2 are following:

(1) $A\Box\ sense(v_0) \rightarrow sense(v_1) \wedge sense(v_5)$

(2) $A\Box\ sense(v_1) \rightarrow sense(v_0) \wedge sense(v_2) \wedge sense(v_4)$

(3) $A\Box\ sense(v_2) \rightarrow sense(v_1) \wedge sense(v_3)$

(4) $A\Box\ sense(v_3) \rightarrow sense(v_2) \wedge sense(v_4)$

(5) $A\Box\ sense(v_4) \rightarrow sense(v_1) \wedge sense(v_3) \wedge sense(v_5)$

(6) $A\Box\ sense(v_5) \rightarrow sense(v_0) \wedge sense(v_4)$

As an example, the transition system of sense pattern M in Figure 1 cant satisfy the third formula. The proof is following.

Proposition 4.1. $M \not\models A\Box\ sense(v_2) \rightarrow sense(v_1) \wedge sense(v_3)$

Proof: There is a transition path p in $M : p =< s_0, l_0, s_1, l_1, s_2, l_2, s_3, l_3, s_4, l_4, s_5, l_5 >^\circ$.

The symbol $^\circ$ means circle, namely the transition path transit from s_0 to s_5 orderly and constantly.

In the sense pattern s_2, only $n_2 = active$.

Obviously:

$< n_2, v_2 > \in R \Rightarrow s_2 \models sense(v_2)$

$< n_2, v_1 >, < n_2, v_3 > \notin R \Rightarrow s_2 \not\models sense(v_1) \wedge s_2 \not\models sense(v_3)$

So:

$s_2 \not\models sense(v_2) \rightarrow sense(v_1) \wedge sense(v_3)$

$\Rightarrow p \not\models \Box\ sense(v_2) \rightarrow sense(v_1) \wedge sense(v_3)$

$\Rightarrow M \not\models A\Box\ sense(v_2) \rightarrow sense(v_1) \wedge sense(v_3)$

Q.E.D

M cant satisfy other formulas too, the proof is similar.

However, when v_2 is sensed, v_1 and v_3 will be sensed eventually. This request can be specified as a formula:

$$A\Box\ sense(v_2) \rightarrow (\Diamond sense(v_1) \wedge \Diamond sense(v_3))$$

Proposition 4.2. $M \models A\Box\ sense(v_2) \rightarrow (\Diamond sense(v_1) \wedge \Diamond sense(v_3))$

Proof: There is a transition path p in $M : p =< s_0, l_0, s_1, l_1, s_2, l_2, s_3, l_3, s_4, l_4, s_5, l_5 >^\circ$.

Obviously, $s_1 \models sense(v_1), s_2 \models sense(v_2), s_3 \models sense(v_3)$

Because s_1 and s_3 can appear after s_2 in path p, $s_2 \models \Diamond sense(v_1) \wedge \Diamond sense(v_3)$.

So, $s_2 \models sense(v_2) \rightarrow (\Diamond sense(v_1) \wedge \Diamond sense(v_3))$.

In path p, s_1 and s_3 will appear after every s_2, so:

$p \models \Box sense(v_2) \rightarrow (\Diamond sense(v_1) \wedge \Diamond sense(v_3))$.

Because there is only one path p in M, so:

$M \models A\Box\ sense(v_2) \rightarrow (\Diamond sense(v_1) \wedge \Diamond sense(v_3))$.

Q.E.D

5. Conclusion.

This paper researches the sense ability and request from the perspective of sense situation of environment elements. It proposes a new type of sense request for WSN which refers to the logic relation, and it gives a framework for analysis which based on formal method. This framework is a formal system, it uses the transition system of sense pattern to specify the sensor scheduling strategy of WSN, and the logic sense request is specified by the temporal logic of sense. By some examples of inference verification, it shows this method is a feasible approach to analyze the logic sense request.

The further researches are following:

(1) The algorithm which verifies whether the transition system of sense pattern satisfies the formula of temporal logic of sense.

(2) The changeable sense relation, namely the environment elements which sensed by a sensor are not fixed. This work enables the TSSP to specify the sensor scheduling strategy of mobile WSN.

(3) The transition with time constraint. This work enables the TSSP to specify real time WSN.

(4) The equivalence of sensors and environment objects. This work can reduce the scale of elements which need to be specified, and the efficiency of modeling and verification will be improved by this work.

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