

## Research Article

# Energy Consumption Evaluation for Wireless Sensor Network Nodes Based on Queuing Petri Net

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Due to the large scale of wireless sensor networks (WSN) and the huge density of WSN nodes, classical performance evaluation techniques face new challenges in view of the complexity and diversity in WSN applications. This paper presents a “state-event-transition” formal description for WSN nodes and proposes an event-driven QPN-based modeling technique to simulate the energy behaviors of nodes. Besides, the framework architecture of a dedicated energy evaluation platform has been introduced, which can be used to simulate the energy consumption of WSN nodes and to evaluate the system lifetime of WSN. Case studies prove that this platform can be utilized for the selection of WSN nodes and network protocols, the deployment of network topology, and the prediction of system lifetime as well.

## 1. Introduction

With the rapid progress of information and communication technologies (ICT) and the wide range of applications in wireless sensor networks (WSN), the performance evaluation and analysis techniques in WSN have made great progress [1, 2]. Classical evaluation techniques, such as the data or bits flow analysis [3], the state transition modeling based on Markov chain [4] and Petri net [5], and the model-driven architecture analysis [6], have to face some new challenges due to the following. On one hand, it is the large scale of wireless sensor networks and the huge amount of WSN nodes, which make the physical testing become very complex when the costs and scales of WSN applications must be taken into account. On the other hand, it is the diversity of system tasks and the complexity of application environments, which make mathematical calculation become extremely complex when considering a large number of time-varying factors, such as network traffics, wireless channels, and network topologies.

In addition, the power state and its transition correlations in most of classical energy models are generally

oversimplified, which normally focuses on RF transceivers but ignoring other components may result in an imprecise evaluation especially when taking into account of the cases with heavy workloads on processors and sensors. Due to the employment of these imprecise models in the simulation tools (such as NS-2/3, SHAWN, and OPNET) [7] or on the evaluation platforms [8–10], the evaluation accuracy is deteriorated and the evaluation scopes of WSN applications are thus constrained.

In this paper, we propose an event-driven queuing Petri net (QPN) model to simulate the energy consumption behaviors of sensor nodes in Section 2. The framework architecture of a dedicated energy consumption evaluation platform is introduced in Section 3. In Section 4, we give some case studies to evaluate the energy consumption of WSN nodes. Finally, we draw the conclusions and present the ongoing works.

## 2. Event-Driven QPN Model of WSN Nodes

WSN nodes adopt the component-based system architecture and the event-driven operation mode. In this paper, we define

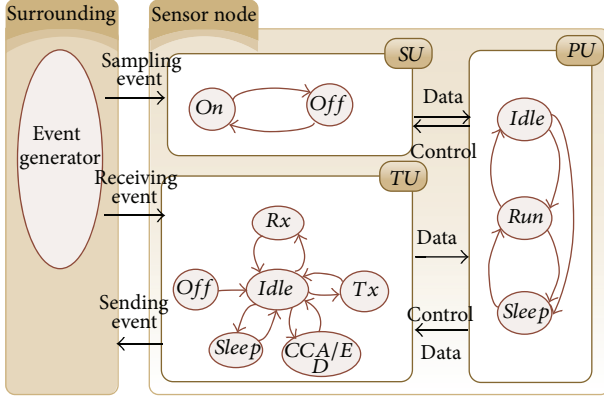


FIGURE 1: Event-driven component correlations in sensor nodes.

TABLE 1: Place definition in the QPN model.

Place class	Place name	Description
State place	ES	Data sampling event generator
	ER	Data receiving event generator
	SD	Data sampling process
	DB	Data waiting process
	MS	PU in sleep state
	MI	PU in wakeup/idle state
	MR	PU running
	TB	Data waiting to send
	RS	TU in sleep state
	RI	TU in wakeup/idle state
	RC	TU channel listening
	RT	Data sending process
	RR	Data receiving process
	Channel	Channel resource
Resource place	MTT	PU sleeping threshold
	RTT	TU sleeping threshold

the  $\langle \text{Transceiver}, \text{Processor}, \text{Sensor} \rangle$  node architecture and the  $\langle \text{state}, \text{event}, \text{transition} \rangle$  system behavior mode.

**2.1. State-Event-Transition Formal Description.** From the view of energy consumption, a WSN node has an energy source (i.e., batteries) and some core components (i.e., PU-microcontroller, TU-RF transceiver, and SU-sensor). Each component has its power states and some preset state transitions. By analyzing the energy behaviors of components, the sensor node is defined as “state-event-transition” (SET), illuminated as follows.

- (i) **State (S).** It indicates the power degrees of a component, which are customizable according to component characteristics, such as TU  $\langle \text{Off}, \text{Idle}, \text{Tx}, \text{Rx}, \text{Sleep}, \text{CCA/E} \rangle$ , PU  $\langle \text{Idle}, \text{Run}, \text{Sleep} \rangle$ , and SU  $\langle \text{On}, \text{Off} \rangle$ .
- (ii) **Event (E).** It reveals the correlations between components as well as between a WSN node with its

TABLE 2: Token definition in QPN model.

Token class	Event class	Token name	Description
Event token	$e_o$	Esc	Periodic sampling
		Esu	Sporadic sampling
		Erd	Data packet receiving
		Erc	Control packet receiving
		Etd	Data packet sending
	$e_b$	Etc	Control packet sending
		Msc	Control signal sampling
		Mrs	Control signal receiving
		Mtc	Control signal sending
		Mtt	PU sleeping timer timeout
	$e_i$	Rtt	TU sleeping timer timeout
		SS	SU state flag
		MS	PU state flag
		RS	TU state flag
State token		Ch	Channel allocation
Resource token			

surrounding. It can be a message, data, or an interruption, and so forth.

- (iii) **Transition (T).** It donates  $\{f(s, e) = s_s - [\text{when event } e \text{ occurs, take an action (operation)}] - > s_d \mid s_s, s_d \in S, e \in E\}$ ; it represents a function set of state transitions driven by events, in which *action* implies energy behaviors of components (i.e., function execution, data sense, etc.). Define  $s_s$  as source state and  $s_d$  as destination state when  $s_s = s_d$ , which means that system does not switch state and just takes an *action*.

In view of the correlations of system operations, *events* are divided into three classes:

- (i) event from outside ( $e_o$ ): it drives the operations of WSN node, which came from its surroundings (e.g., collecting data via SU or receiving packet via TU);
- (ii) event between components ( $e_b$ ): it drives the successive actions between components (e.g., data transferring, signal controlling, etc.);
- (iii) event within a component ( $e_i$ ): it triggers state transitions within components (e.g., timer timeout).

Figure 1 shows the event-driven correlations in sensor nodes, in which WSN nodes interact with the surroundings via TU and SU. The environmental data are collected in SU and are processed in PU and finally being transmitted via TU. Moreover, the packets (carriers) sent from other WSN nodes are detected in TU and then being processed in PU according to the packet types.

**2.2. QPN Energy Model of Sensor Nodes.** Nowadays different techniques are used to evaluate the energy consumption of WSN node: stochastic analysis [11], finite state machine [12], color Petri net [13], and formal and analytical model [14]. In this work, we adopt queuing Petri net (QPN) [15] because

```

//R1: states transform
{
  For each state  $s, s \in S$ , define a place  $p_s$  in QPN,  $p_s \in P$ ;
  For every  $p$ , initialize the power propertyies with the power of
  component in state  $s$ .
}

//R2: transitions transform
{
  For each transitions  $f(s, e) \in T_{SET}$ 
  {
    Define a transition  $t$  in QPN,  $t \in T_{QPN}$ .
    Add a queue related to event  $e$  in place  $p_{ss}$  ( $p_{ss}$  are determined by rule R1);
    Initialize the service time of event  $e$  in the two queues;
    If  $s_s = s_d$  {
      Add double arrow between transition  $t$  and state  $s_s$ 
    }Else{
      Add an arrow  $a_1$  from  $s_s$  to transition  $t$ , and an arrow  $a_2$  from transition  $t$  to  $s_d$ ;
      Initialize the time property of arrow  $a_1$  and  $a_2$  with (transition time)/2;
    }
  }
}

```

LISTING 1: Mapping rules between SET and QPN.

from our point of view, QPN is more appropriate to represent the event-driven based operations of WSN and easier to describe the service queue behavior. Notice that the popular TinyOS and Contiki are event-driven WSN operating system. In order to minimize energy consumption, most of the WSN adopt *sleep* and *wakeup* and duty cycle operation modes which may be easily modeled by a finite state machine or QPN. In comparison with the existing techniques, we propose a versatile technique which enables simulating easily any WSN platform (e.g., TinyOS, Contiki, etc.).

Consequently in this paper, we adopt QPN by combining the functions and features of queuing theory and Petri net model to describe system architectures and its scheduling strategies. A 4-tuple QPN  $\langle P, T, F, M \rangle$  is defined to model the “SET” description, shown in Listing 1.

- (i)  $P$  (Place). It represents resources or states, which provides interaction spaces between WSN nodes (components) with its surroundings.
- (ii)  $M$  (Token). It indicates event occurrences in “Place”, which is continuously activated during transitions.
- (iii)  $T$  (Transition). It indicates state transition actions of WSN node components, while events drive actions resulting in state transitions.
- (iv)  $F$  (A set of directed arcs). It describes conditions and influences of state transitions, which can be defined as  $F \subseteq (S \times T) \cup (T \times S)$ .

In order to evaluate the energy consumption of SET system, several time relative parameters are defined in the QPN model as the properties of power states, that is, wait time, service time, and residence time, which are used to estimate the time duration that a WSN node (component)

operates in a power state. For most of WSN nodes, there is a single core processor and a RF transceiver; thus, we can suppose that only a unique service provider exists in a *place*. Generally, as the WSN node has low workload, the component’s service rate is always larger than events arrival rate, which means that the event queue can be simplified as an infinite queue. Furthermore, since the wait time that *tokens* arrive at a *place* is uncertain and the service time is generally determined, the G/D/1 queue model assumptions can be established.

### 2.2.1. Definition of QPN Energy Model

(A) *Place*. In the QPN model, two classes of *places* (shown in Table 1) are defined: *state place*, also known as *queue place*, represents a power state of WSN nodes (components); *resource place* provides resources to simulate event-driven behaviors or generate activation condition.

(B) *Token*. In the QPN model, three classes of *tokens* (shown in Table 2) are proposed: *event token* corresponds to events in SET; *state token* provides “customer” under nonoperation states; *resource token* provides the channel allocation.

(C) *Transition*. In the QPN model, *transition* reveals system operations of WSN nodes through *tokens* migration within *places*, which resulted in state changes. Define *transition* rules as follows:

- (i)  $aP_i(t_i) + bP_j(t_j) \rightarrow cP_m(t_m) + dP_n(t_n)$ . When transition occurs, place  $P_i$  destroys tokens  $a * t_i$  and  $P_j$  destroys  $b * t_j$ , and then  $P_m$  and  $P_n$  issue tokens  $c * t_m$  and  $d * t_n$ , respectively;

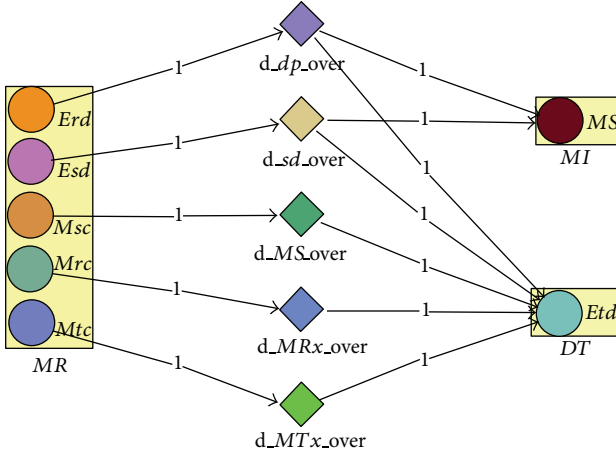


FIGURE 2: Graphical modeling instantiation of 6th transition:  $p\_Tx\_data$ .

- (ii)  $P_i(t_i) \rightarrow NULL$ . If all token  $t_i$  in  $P_i$  is destroyed and no new token is generated, then  $P_i$  is empty.

The QPN model declares 19 *transitions* to describe the correlations among components, nodes, and its surroundings based on *tokens* and *places*. Giving an example to illuminate state transition, for example, the 6th *transition*, termed  $p\_Tx\_data$ , contains two operation modes: (1) data processing; the *transition* expression is  $MR(t_i) \rightarrow DT(Etd) + MI(MS)$ ; (2) packet controlling; the expression is  $MR(t_i) \rightarrow MI(MS)$ . The *transition* descriptions are as follows: after data processing,  $PU$  will enter *idle* state, and the processed data will be sent into the transferring queue buffer or to perform control signal processing. Figure 2 shows the graphical modeling instantiation of 6th transition  $p\_Tx\_data$ .

**2.2.2. Instantiation of QPN Energy Model.** Based on the model definitions of the 4-tuple QPN  $\langle P, T, F, M \rangle$ , the QPN energy model is instantiated based on the QPME emulator [16], shown in Figure 3. This instantiation contains three main function blocks  $\langle SU, PU, and TU \rangle$  and two event sources  $\langle ES, ER \rangle$  which generates the continuous event *tokens* to drive the model operation of sensor nodes.

### 3. Energy Evaluation Platform Based on QPN Model

**3.1. Framework of Energy Evaluation Platform.** Based on the QPN model, a dedicated energy evaluation platform is designed for WSN nodes, shown in Figure 4, which consists of two main components: an event generator and the QPN energy simulator.

This paper aims to propose a common platform for energy evaluation of WSN nodes, which must cover the differences in the *HW* and *SW* architecture, diversified tasks, and complex environments. From our point of view, on one hand, the runtime environments and tasks determine the occurrence frequency and the success rate of *events*; on the

other hand, system architecture and its strategies have a significant impact on energy consumptions of WSN nodes.

The event generator can generate event sequences similar to the real scenarios, which allows users to customize the runtime characteristics of environments and tasks, and the system architecture and its strategies as well. The customized information is sent to the network simulation engine (i.e., NS-2) and then the event sequences can be achieved as the simulation outputs.

**3.2. Evaluation Methodology of Energy Consumption.** Several hypotheses are proposed to simplify the energy consumption calculation of WSN nodes: (1) energy source (i.e., battery) has the linear charge and discharge characteristics without regard to recharge issues. (2) Energy consumption of WSN node ( $E_{node}$ ) is the accumulation result of that of its components ( $E_{com}$ ); that is,  $E_{node} = \sum E_{com}$ . (3) Energy consumption of components contains event execution within *places* ( $E_S$ ) and state transition between *places* ( $E_T$ ); that is,  $E_{com} = E_S + E_T$ .

From the view of the QPN model, events drive system operations and then result in energy consumption of sensor nodes. Considering an event  $e$  in a place  $p$ , to analyze its energy consumption, we need to count the four parameters: the operation time ( $t_s$ ) and the mean power consumption ( $p_s$ ) of *tokens* in *places*; that is,  $E_S = \sum (p_s * t_s)$ ; the occurrence frequency ( $c_t$ ) and its mean energy consumption ( $e_t$ ) of a state transition, that is,  $E_T = \sum (e_t * c_t)$ , are shown in

$$E_T = \sum_{i \in T} e_t * c_t = \sum_{i \in T} \frac{(p_{s_1} + p_{s_2}) * t_t * c_t}{2}. \quad (1)$$

Assuming that the conversion time of state transition is termed as  $t_t$ , the power of state before transition is  $p_{s_1}$ , the power of state after transition is  $p_{s_2}$ , and the energy consumption  $e_t = p_{s_1} * t_t / 2 + p_{s_2} * t_t / 2 = (p_{s_1} + p_{s_2}) / 2 * t_t$ . Hence, the energy consumption of WSN node can be expressed as (2), in which the power parameters  $p_s$  and the time parameters of state transition ( $t_t$ ) are generally constants, which are obtained from physical tests or hardware datasheets. Therefore, the key issue of the energy evaluation is to count the time variable  $t_s$  and the frequency variable  $c_t$ , which can be obtained from the QPN model simulation

$$\begin{aligned} E_{node} &= \sum E_{com} = E_{SU} + E_{PU} + E_{TU} = \sum (E_S + E_T) \\ &= \sum \left( \sum_{i \in S} p_s * t_s + \sum_{i \in T} e_t * c_t \right) \\ &= \sum \left( \sum_{i \in S} p_s * t_s + \sum_{i \in T} \frac{(p_{s_1} + p_{s_2}) * t_t * c_t}{2} \right). \end{aligned} \quad (2)$$

### 4. Energy Evaluation of Sensor Nodes: Case Studies

This QPN model is instantiated on the QPME emulator [16]. Some case studies are investigated to evaluate this model, including the energy evaluation and lifetime prediction of

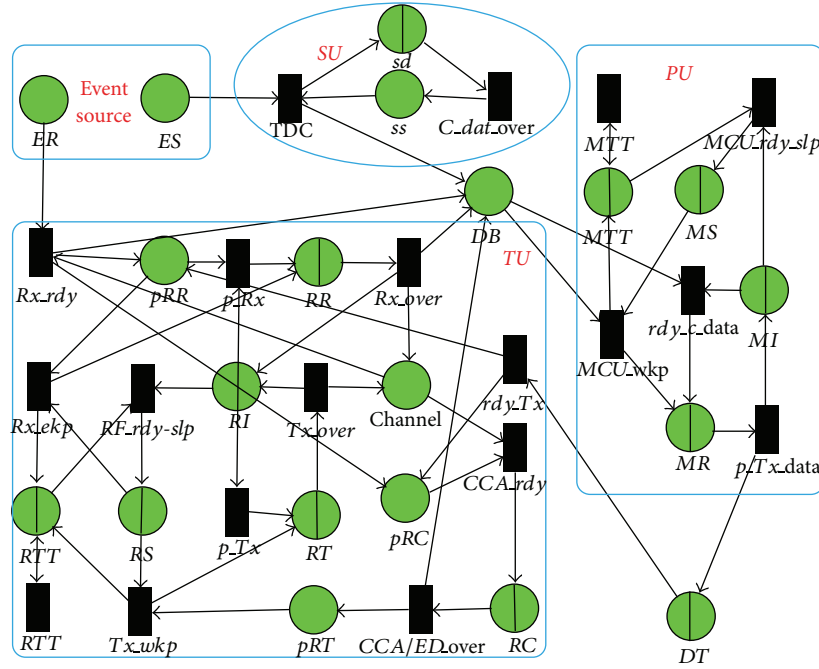


FIGURE 3: QPN model implementation on QPME.

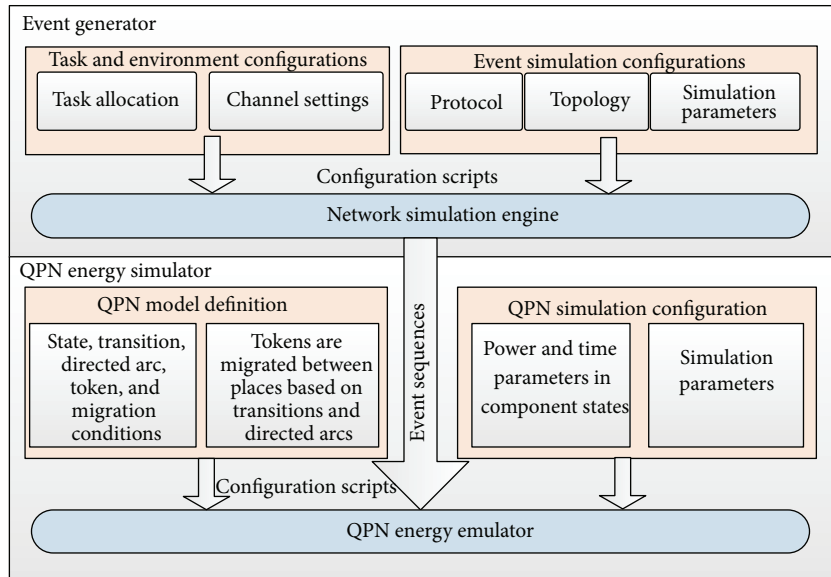


FIGURE 4: Framework of energy evaluation platform for WSN nodes.

WSN nodes. The obtained results are compared with other approaches ones.

#### 4.1. Energy Consumption Evaluation of WSN Node

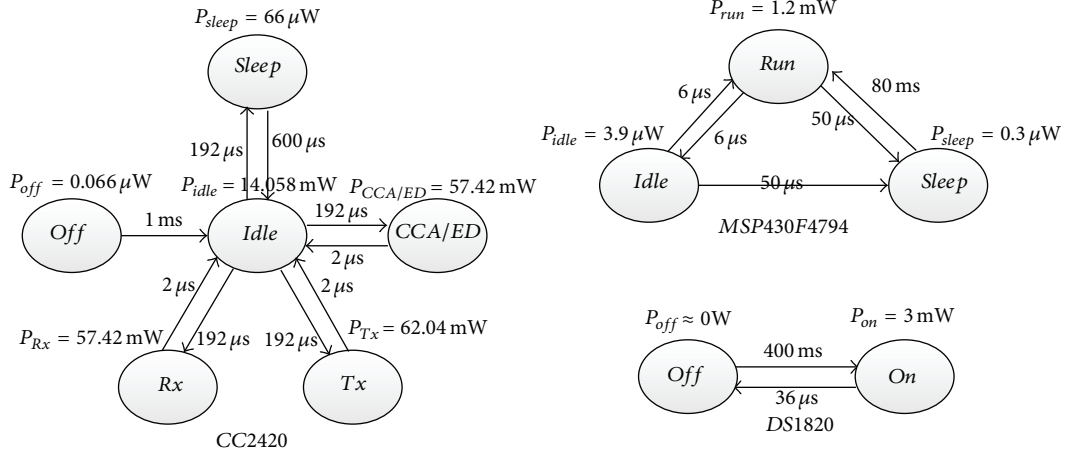
**4.1.1. Node Architecture and Simulation Conditions.** The energy evaluation platform allows users to customize the architecture of WSN nodes and configure the simulation conditions according to requirements. In this case study, we suppose a WSN node (i.e., telos, termed  $N_A$ ) that consists of a microcontroller-MSP430F4794 (PU), a transceiver-CC2420

(TU), and a temperature sensor-Dallas Semi.DS1820 (SU). The parameters of components and the state transitions of nodes are obtained from datasheets as illustrated in Figure 5.

Three simulation tests are performed which aim to compare the energy consumption of WSN nodes in different workload models, described in Table 3.

**4.1.2. Simulation Results and Analysis.** The two statistical parameters, the operation time ( $t_s$ ) in a state and the conversion number ( $c_i$ ) of a state transition, can be achieved through the simulation of the QPN model on



FIGURE 5: Performance parameters and the state relationship in node  $N_A$ .TABLE 3: Simulation conditions in  $N_A$ .

Parameter configuration	Test 1	Test 2	Test 3
Simulation time		600 s	
CPU clock frequency		1 Mhz	
System power supply		3 V	
Data transfer rate		100 kbps	
Data sampling resolutions		12 bit	
Sleeping time threshold in PU		3 s	
Packet arriving time interval	5 s	2.5 s	
Sensor sampling period	20 s		5 s

TABLE 5: Simulation conditions in  $N_A$  and  $N_B$ .

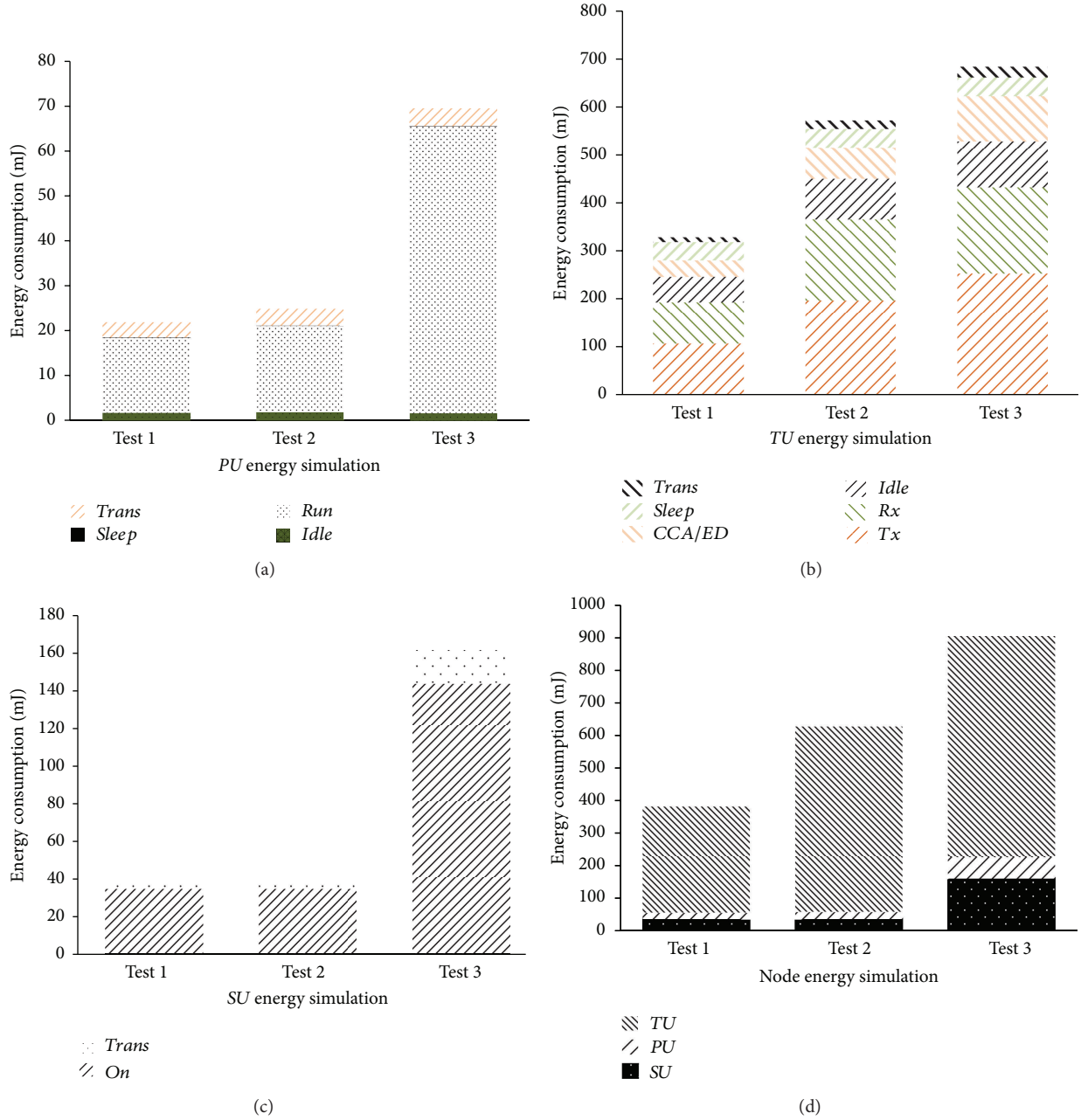
Parameter configuration	Test 1	Test 4	Test 5
Sensor node	$N_A$	$N_B$	
CPU clock frequency	1 Mhz	4 MHz	
Data transfer rate	100 kbps	38.4 kbps	
Sleeping time threshold in PU	3 s		0.1 s
Simulation time		600 s	
System power supply		3 V	
Data sampling resolutions		12 bit	
Packet arriving time interval		5 s	
Sensor sampling period		20 s	

TABLE 4: Simulation results of energy consumption in  $N_A$ .

Components	States	Test 1 (mJ)	Test 2 (mJ)	Test 3 (mJ)
PU	<i>Idle</i>	1.639	1.812	1.582
	<i>Run</i>	16.681	19.114	63.821
	<i>Sleep</i>	0.049	0.035	0.043
	$E_{T\_PU}$	0.7227	7.16	3.75
	$E_{com\_PU}$	7.5467	24.32	24.71
SU	<i>On</i>	34.8	34.8	144
	<i>Off</i>	0	0	0
	$E_{T\_SU}$	4.35	4.35	4.35
	$E_{com\_SU}$	39.15	39.15	39.15
TU	<i>Idle</i>	53.094	83.673	95.954
	<i>Tx</i>	107.329	197.287	253.123
	<i>Rx</i>	86.015	169.274	179.150
	<i>CCA/ED</i>	34.736	64.561	94.467
	<i>Sleep</i>	38.917	38.747	38.670
	<i>Off</i>	0	0	0
	$E_{T\_TU}$	9.51	17.99	21.58
	$E_{com\_TU}$	329.60	571.53	682.95
Node	$E_{com}$	390.49	635.39	914.44

TABLE 6: Energy consumption in  $N_A$  and  $N_B$ .

Components	States	Test 1 (mJ)	Test 4 (mJ)	Test 5 (mJ)
PU	<i>Idle</i>	1.639	2434.2	141.6
	<i>Run</i>	16.681	258.6	258.6
	<i>Sleep</i>	0.049	2.1	13.5
	$E_{T\_PU}$	0.7227	37.3	72.7
	$E_{com\_PU}$	7.5467	2732.2	486.4
SU	<i>On</i>	34.8	34.8	34.8
	<i>Off</i>	0	0	0
	$E_{T\_SU}$	4.35	4.35	4.35
	$E_{com\_SU}$	39.15	39.15	39.15
TU	<i>Idle</i>	53.094	146.9	146.9
	<i>Tx</i>	107.329	222.7	222.7
	<i>Rx</i>	86.015	112.3	112.3
	<i>CCA/ED</i>	34.736	—	—
	<i>Sleep</i>	38.917	1.76	1.76
	<i>Off</i>	0	0	0
	$E_{T\_TU}$	9.51	8.28	8.28
	$E_{com\_TU}$	329.60	490.2	490.2
Node	$E_{com}$	390.49	3261.6	1015.85

FIGURE 6: Simulation results of energy consumption in  $N_A$ .

the evaluation platform. Notice that the energy values, that is,  $E_S$ ,  $E_T$ , and  $E_{\text{node}}$ , can be obtained in (2), shown in Table 4.

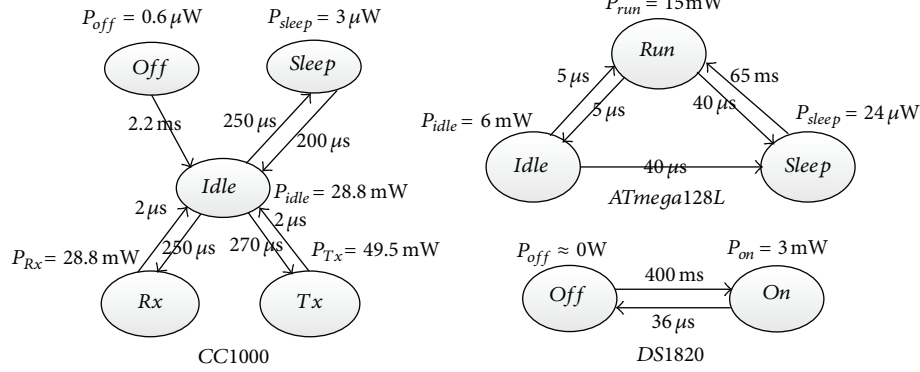
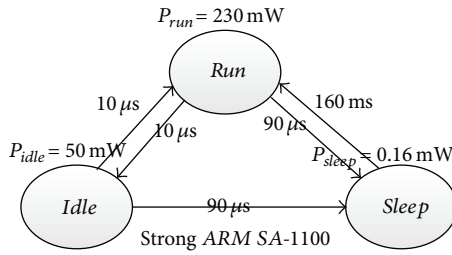
The evaluation results under different simulation conditions are shown in Figure 6. Some conclusions can thus be summarized as follows.

In WSN applications, those nodes surrounding the sink node or the cluster-head node in general consume more energy due to the higher arrival rate of data packet comparing with others, which may lead to the phenomenon of “surveillance holes”. In test 1 and test 2, different rates of packet arrival are proposed to evaluate the balanced energy consumption issue of WSN. Moreover, different task

models generate different workloads that lead to different energy consumption. In test 2 and test 3, different sampling frequencies of SU are proposed to evaluate the workload influences on energy consumption of nodes.

In Figure 6, because test 2 has the double rate of packet arrive than test 1, the WSN node in test 2 thus has higher energy consumption; because test 3 has the four times of sampling frequency than test 1, the WSN node in test 3 thus has higher energy consumption as well.

**4.1.3. Simulation Comparison Based on Node Architecture.** In order to evaluate the influence of node architecture on energy consumption, assume another WSN node (i.e., Mica2, termed

FIGURE 7: Performance parameters and the state relationship in node  $N_B$ .FIGURE 8: Power and time parameters in PU component of  $N_C$ .

$N_B$ ) with a PU component *Atmega 128L* and a TU component *CC1000*. Figure 7 shows the node parameters and Table 5 shows the simulation conditions of tests.

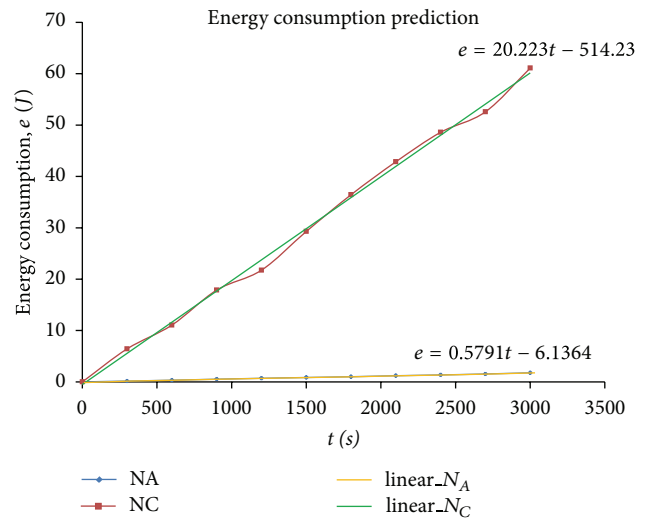
The energy results are obtained based on the QPN model simulation, shown in Table 6. Some conclusions can be summarized as follows.

As an event-driven system, most of WSN node components enter the low-power state to save energy when no event occurs. In Table 6, test 4 and test 5 show the energy evaluation in  $N_B$  with different sleeping time thresholds. The energy consumption in test 4 is significantly greater than the one in test 5, which proves that the time threshold of 0.1 s is more suitable for  $N_B$  and this simulation scenario. However, it should be noted that more energy consumption may occur due to the frequent state transitions as the result of improper threshold value setting.

Comparing with the results in test 1 ( $N_A$ ) and test 5 ( $N_B$ ), we found that the node  $N_A$  (telos) has less energy consumption than the node  $N_B$  (Mica2). In the same simulation scenario,  $N_A$  has only one-third of the energy consumption in  $N_B$ , which is due to the main functional components of  $N_A$  (i.e., PU-MSP430 and TU-CC2420) that have more optimal low-power operation modes than those of  $N_B$  (PU-*Atmega128L* and TU-CC1000).

#### 4.2. Lifetime Prediction of WSN Node

**4.2.1. Node Architecture and Simulation Conditions.** In WSN applications, the lifetime of WSN node is a key parameter for the protocol selection and topology deployment, which

FIGURE 9: Energy prediction of WSN nodes ( $N_A$  and  $N_C$ ).TABLE 7: Simulation conditions in  $N_C$ .

Parameter configuration	Test 6	Test 7
Sensor node	$N_A$	$N_C$
CPU clock frequency	1 MHz	133 Mhz
Sleeping time threshold in PU	1 s	0.1 s
Simulation number		10
Simulation time		300 s
System power supply		3 V
Sensor sampling period		30 s
Data transfer rate		100 kbps
Data sampling resolutions		12 bit
Packet arriving distribution	<i>Exponential distribution</i> ( $\lambda = 0.5$ )	

is predictable based on the QPN simulation and energy evaluation. In order to evaluate the lifetime of WSN node, assuming another WSN node (termed  $N_C$ ), which has different PU component *ARM SA-1100* comparing to the node  $N_A$ , Figure 8 shows the parameters of the node  $N_C$  and Table 7 shows its simulation conditions.



TABLE 8: Simulation conditions based on QPN and NS-2.

Parameter configuration	
WSN node	$N_A$ (1 Mhz)
Simulation time	3000 s
System power supply	3 V
Sensor sampling period	30 s
Data transfer rate	100 kbps
Data sampling resolutions	12 bit
Sleeping time threshold in $PU$	1 s
Packet arriving distribution	Exponential distribution ( $\lambda = 0.2$ )

TABLE 9: Simulation and test conditions in  $N_D$ .

Parameter configuration	
Sensor node	8051
Simulation time	10 days
System power supply	3 V (2 * AA batteries)
Sensor sampling period	600 s
Data transfer rate	100 kbps
Data sampling resolutions	12 bit
Sleeping time threshold in $PU$	0.1 s
Packet arriving distribution	Exponential distribution ( $\lambda = 0.005$ )

**4.2.2. Simulation Results and Analysis.** Figure 9 shows the energy prediction of WSN nodes, in which the linear approximation functions of node energy consumption are  $e = 0.579t - 6.1364$  ( $N_A$ ) and  $e = 20.223t - 514.23$  ( $N_C$ ), respectively, that means that the energy consumption of WSN nodes is increased linearly with the time duration.

Based on the linear functions, the lifetime of WSN node can be predicted. Suppose that an energy source of WSN node is 100 J and the operation scenario is described in Table 7; then, the lifetimes of  $N_A$  and  $N_C$  are estimated as 48.6 h and 1.38 h, respectively. To verify this prediction, a same simulation condition is described except that the simulation times of WSN nodes are configured as the predictable results, that is, 48.6 h ( $N_A$ ) and 1.38 h ( $N_C$ ); then, the simulation results of  $N_A$  and  $N_C$  are almost 100 J, shown in Figure 10. Meanwhile, because  $PU$  in  $N_A$  is ultralow power, the main energy consumption of  $N_A$  is in  $TU$ , while in  $N_C$ , most of energy is consumed by  $PU$  due to its relatively high power consumption attributes and improper sleeping time threshold setting.

**4.3. Comparison and Verification with Other Approaches.** In order to evaluate this QPN model, we compare the simulation results with other evaluation approaches.

**4.3.1. Comparing with NS-2 Simulation.** In [17], an energy model is developed to replace the original energy model in NS-2, which can be used to compare with this QPN model, given the same simulation environment defined in Table 8.

The result comparisons of energy consumption based on QPN and NS-2 are shown in Figures 11 and 12, illustrated as follows. (1) The two energy curves in QPN and NS-2

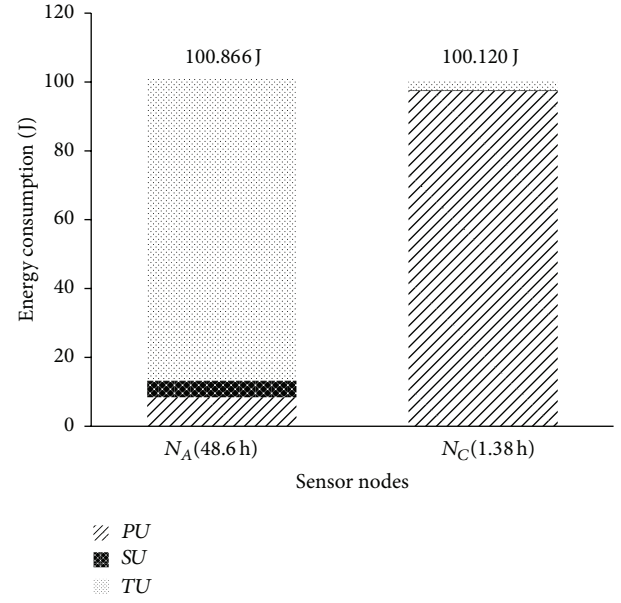


FIGURE 10: Lifetime prediction of WSN nodes.

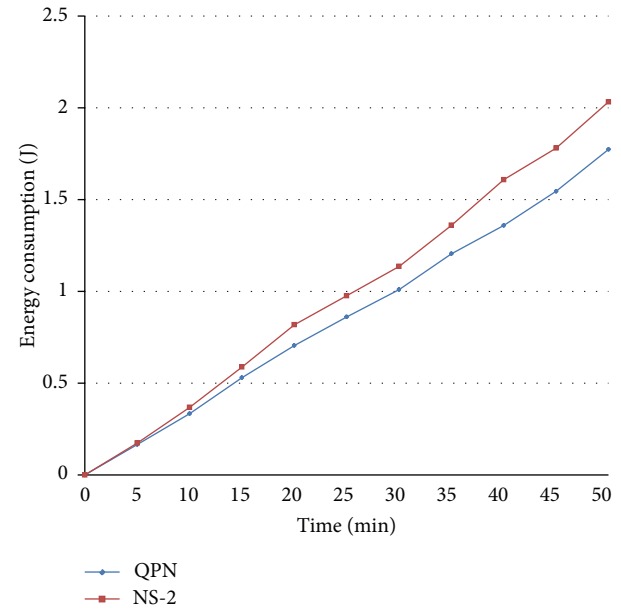


FIGURE 11: Comparisons of node energy consumption based on QPN and NS-2.

are linear approximation and the simulation results are thus approximate; (2)  $TU$  in NS-2 consumes more energy than in QPN because the wireless channel model and the control packets are considered in the energy evaluation of NS-2, which make the NS-2 simulation more precise.

**4.3.2. Comparing with Physical Measure.** The physical measure is performed to verify the performance of QPN model. The target node is CC2430 (termed  $N_D$ ), which consists of a  $PU$ -8051, a  $TU$ -CC2420, and a  $SU$ -AD Converter, shown in Figure 13.

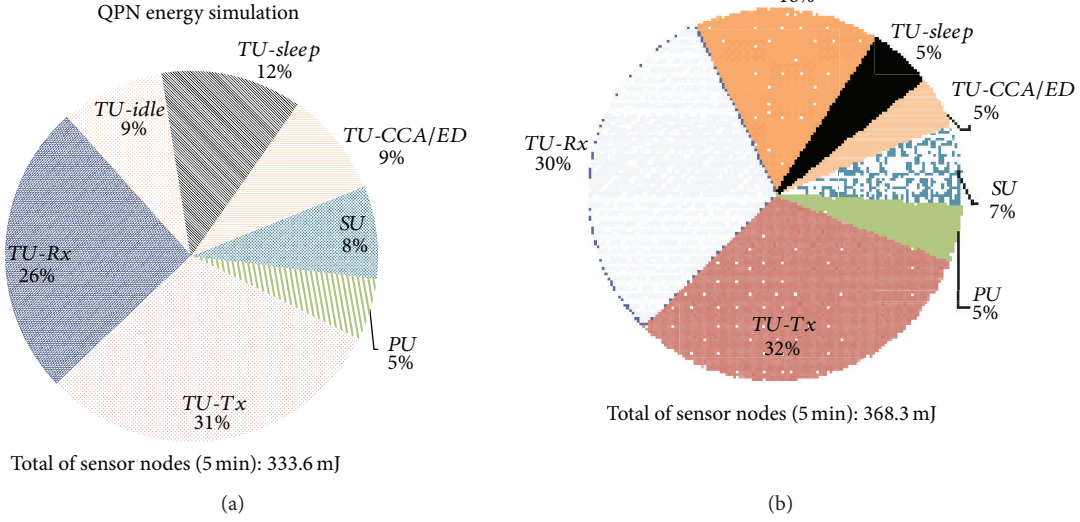


FIGURE 12: Comparisons of component energy consumption based on QPN and NS-2.



FIGURE 13: Prototype of sensor node CC2430.

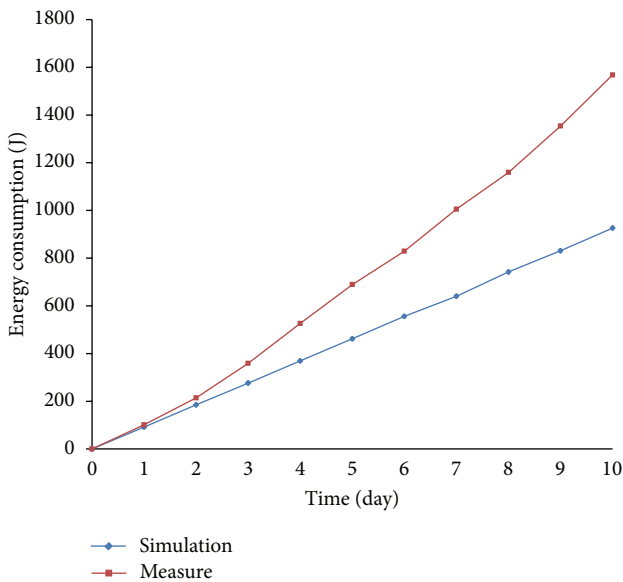


FIGURE 14: Energy evaluation in model simulation and physical measure.

Table 9 defines the simulation and test scenario and the initial capacity of battery is 10.8 KJ. The test approach refers to [18], and the physical test is performed per hour to measure the battery capacity at the moments.

Figure 14 shows the energy comparison between the QPN simulation and physical test. The results show that the QPN simulation has the similar energy tendency and its energy curve is close to the actual energy consumption. However, in Figure 14, the energy curves also expose the widening gap with the time duration. Assuming that the failure threshold of battery capacity is 50 J, the estimation lifetime of WSN nodes is 234.8 days according to the QPN simulation curve but only 176 days according to the measurement curve. The main reasons resulting in the gap include the power consumption of hardware circuits, the nonlinear discharge characteristics of battery, imprecise measurement method, and so forth. In view of the electromagnetic discharge curve and the conclusions in [18], we can confirm that the difference is reasonable.

## 5. Conclusions

At present, the “state-event-transition” formal descriptions for the energy behaviors of WSN nodes are defined, and the event-driven QPN model is proposed and instantiated on QPME. Besides, a dedicated energy consumption evaluation platform based on the QPN model is implemented, on which some cases studied are investigated to evaluate the energy consumption of WSN nodes and to predict the lifetime of WSN. The evaluation results prove that this platform can be utilized for the selection of WSN nodes and protocols, the deployment of network topology, and the evaluation of system lifetime as well.

In order to improve the accuracy and efficiency for this QPN model, the ongoing works focus on the following topics: (1) to obtain accurate power and time parameters of components and the capacity of batteries; the testing platform and benchmarks are being designed to measure energy consumption of WSN nodes; (2) to compare with the performance results obtained from other approaches; the simulation approach based on network simulation tools and the physical testing approach are adopted to validate the accuracy of this model; and (3) to analyze energy consumption of WSN; based on this QPN model, the energy consumption of WSN are modelled to evaluated the system lifetime and then to predict the evolution of WSN system in the future.

### Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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