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...
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 \( TU \) \{Off, Idle, Tx, Rx, Sleep, CCA/ED\}, \( PU \) \{Idle, Run, Sleep\}, and \( SU \) \{On, Off\}.

(ii) Event \( (E) \). It reveals the correlations between components as well as between a WSN node with its surrounding. It can be a message, data, or an interruption, and so forth.

(iii) Transition \( (T) \). It donates \( \{ f(s,e) = s' \text{ when event e occurs, take an action (operation) } \} \rightarrow s' \mid s, s' \in S, e \in E \}; it represents a function set of state transitions driven by events, in which \textit{action} implies energy behaviors of components (i.e., function execution, data sense, etc.). Define \( s \) as source state and \( s' \) as destination state when \( s = s' \), which means that system does not switch state and just takes an \textit{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...
In order to minimize energy consumption, most of the 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 \( a \cdot t_i \) and \( P_j \) destroys \( b \cdot t_j \), and then \( P_m \) and \( P_n \) issue tokens \( c \cdot t_m \) and \( d \cdot t_n \), respectively;

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 \textit{sleep} and \textit{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 \((P, T, F, M)\) is defined to model the "SET" description, shown in Listing 1.

```plaintext
//R1: states transform
{
    For each state \( s \), \( s \in S \), define a place \( p_s \) in QPN, \( p_s \in P \);
    For every \( p_s \), initialize the power properties 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 \( p_s \) (\( p_s \) are determined by rule R1);
        Initialize the service time of event \( e \) in the two queues;
        If \( s_i = s_j \)
            Add double arrow between transition \( t \) and state \( s_i \);
        else
            Add an arrow \( a_i \) from \( s_i \) to transition \( t \), and an arrow \( a_j \) from transition \( t \) to \( s_j \);
        Initialize the time property of arrow \( a_i \) and \( a_j \) with \((\text{transition time})/2\);
    }
}
```

Listing 1: Mapping rules between SET and QPN.
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 ($E_{\text{node}}$) is the accumulation result of that of its components ($E_{\text{com}}$); that is, $E_{\text{node}} = \sum E_{\text{com}}$. (3) Energy consumption of components contains event execution within places ($E_{\text{p}}$) and state transition between places ($E_{\text{T}}$); that is, $E_{\text{com}} = E_{\text{S}} + E_{\text{T}}$.

From the view of the QPN model, events drive system operations and then result in energy consumption of sensor nodes. Considering an event ein a place $p$, to analyze its energy consumption, we need to count the four parameters: the operation time ($t_1$) and the mean power consumption ($p_1$) of tokens in places; that is, $E_S = \sum (p_1 \cdot t_1)$; the occurrence frequency ($c_1$) and its mean energy consumption ($e_1$) of a state transition, that is, $E_T = \sum (e_1 \cdot c_1)$, are shown in

$$E_T = \sum_{i \in T} e_i \cdot c_i = \sum_{i \in T} \left( \frac{p_1 + p_2}{2} \right) \cdot t_1 \cdot c_i \cdot \frac{1}{2} \cdot t_1 \cdot c_i.$$  

Assuming that the conversion time of state transition is termed as $t_1$, the power of state before transition is $p_1$, the power of state after transition is $p_2$, and the energy consumption $e_i = p_1 \cdot t_1 / 2 + p_2 \cdot t_2 / 2 = (p_1 + p_2) / 2 \cdot t_1$. Hence, the energy consumption of WSN node can be expressed as (2), in which the power parameters $p$ and the time parameters of state transition ($t_i$) 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 $t_i$ and the frequency variable $c_i$, which can be obtained from the QPN model simulation

$$E_{\text{node}} = \sum E_{\text{com}} = E_{\text{S}} + E_{\text{T}} = \sum (E_S + E_T)$$

$$= \sum \left( \sum_{i \in S} p_i \cdot t_i + \sum_{i \in T} e_i \cdot c_i \cdot \frac{1}{2} \cdot t_1 \cdot c_i \right) \quad \text{(2)}$$

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...
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 ($c_t$) of a state transition, can be achieved through the simulation of the QPN model on
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 4: Simulation results of energy consumption in \( N_A \).

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

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 6: Energy consumption in \( N_A \) and \( N_B \).

| Components | States | Test 1 (mJ) | Test 4 (mJ) | Test 5 (mJ) |
|------------|--------|-------------|-------------|-------------|
| \( E_{S,PU} \) | Idle   | 1.639       | 2434.2      | 141.6       |
| \( E_{S,PU} \) | Run    | 16.681      | 258.6       | 258.6       |
| \( E_{T,PU} \) | Sleep  | 0.049       | 2.1         | 13.5        |
| \( E_{S,PU} \) |          | 0.7227      | 37.3        | 72.7        |
| \( E_{com,PU} \) |        | 7.5467      | 2732.2      | 486.4       |
| \( E_{S,SU} \) | On     | 34.8        | 34.8        | 34.8        |
| \( E_{S,SU} \) | Off    | 0           | 0           | 0           |
| \( E_{T,SU} \) |        | 4.35        | 4.35        | 4.35        |
| \( E_{com,SU} \) |        | 39.15       | 39.15       | 39.15       |
| \( E_{S,TU} \) | Idle   | 53.094      | 146.9       | 146.9       |
| \( E_{S,TU} \) | Tx     | 107.329     | 222.7       | 222.7       |
| \( E_{S,TU} \) | Rx     | 86.015      | 112.3       | 112.3       |
| \( E_{S,TU} \) | CCA/ED | 34.736      | —           | —           |
| \( E_{S,TU} \) | Sleep  | 38.917      | 1.76        | 1.76        |
| \( E_{S,TU} \) | Off    | 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 |
the evaluation platform. Notice that the energy values, that is, $E_S$, $E_T$, and $E_{node}$, 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 $N_B$.

$N_B$) 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 0.1s 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 8 shows the parameters of the node $N_C$ and Table 7 shows its simulation conditions.

| 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 | Exponential distribution ($\lambda = 0.5$) |     |

Figure 9: Energy prediction of WSN nodes ($N_A$ and $N_C$).
Table 8: Simulation conditions based on QPN and NS-2.

| Parameter configuration | \(N_A\) (1 Mhz) |
|-------------------------|------------------|
| WSN node                |                  |
| 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 | \(8051\) |
|-------------------------|----------|
| Sensor node             | \(N_A\) |
| 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 \(e = 0.579t - 6.1364\) for \(N_A\) and \(e = 20.223t - 514.23\) for \(N_C\), 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 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 measurement 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.
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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