

Analysis of Wireless Sensor Networks Based on Energy Consumption Model

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Abstract: A network protocol level framework was built for the simulation of the node energy consumption model. Through examining the energy consumption of different processor modules and communication modules, processor and communication equipment with the lowest energy consumption have been identified. The energy consumption of sensing modules has been discussed during different sensing periods, verifying that sensing period is inversely related to energy consumption. In order to find the key state for energy-saving, this paper analyzed the energy consumption of processor and communication modules in various states. In addition, the components of node energy consumption have been explored, revealing that the communication module accounts for the largest proportion of the node energy consumption and exerts the most significant effect on the node. Copyright © 2013 IFSA.

Keywords: Wireless sensor network, Node energy consumption model, Simulation.

1. Introduction

With the rapid development of embedded systems, wireless communications, networking and micro-mechanical systems, wireless sensor networks (WSN) have caused great concern [1]. A wireless sensor network is constituted in a self-organized manner, which is able to sense and capture physical phenomenon interested in surrounding environments, and to process these information. Wireless sensor networks have wide application in military, environment protection, medical treatment, and commercial areas; for example, wireless sensor networks can be used to monitor enemy troops, equipment and terrains, and can be used to determine pollutant type, concentration, location, etc. [2]. Wireless sensor networks are becoming an indispensable part of information transmission in the future.

Currently, the basic theory of wireless sensor networks is still not complicated; a system model that is able to accurately reflect the characteristics of wireless sensor networks is absent; and studies on bottom layer modeling techniques and evaluation methods for energy consumption are limited [3]. Research on wireless sensor network system modeling and simulation is still in infancy. Most research works have been focused on a variety of communication protocols, whereas studies of bottom layer modeling for platforms and protocols are relatively few [4].

Wireless sensor networks usually run in harsh and dangerous environment remotely, therefore, energy supply is extremely limited due to it cannot be replaced. Sensors in the network are often failed due to energy run-out, so energy issue is the core issue in wireless sensor networks [5]. Current energy models are always designed from the perspective of communication modules or processors, which is lack

of overall analysis and evaluation on energy consumption of the entire system. So, a model that can accurately describe the energy situation of sensor nodes is critical [6]. In this article, the modeling and simulation of energy consumption of nodes in wireless sensor networks will be examined, to provide accurate system base model and assessment methods for existing network simulation tools [7].

2. Energy Consumption Model of Wireless Sensor Nodes

Traditional node energy consumption modeling approach is to deduce the energy consumption of concerned nodes based on theoretical energy consumption data or theoretical models [8]. This method is failed to analyze the energy condition of each energy-consumption modules (communication modules, microprocessors, sensors) comprehensively under different operating modes. Here we will reveal the changes of each energy-consuming equipment and establish energy consumption models for processor modules, communication modules and sensing modules, to analyze the energy consumption status of each module in the running state and the transferring state [9]. Based on this, an overall node energy consumption model is established according to the linkages between each energy module.

2.1. Node Energy Consumption Calculation Model

The processor work state transition model has three states: running state, idle state, and sleep state. Running state is the normal state of the processor, during which, instructions are executed by the processor, and all modules are running. At the idle state, only part of these modules is in operation, reducing part of the energy consumption [10]. At the sleep state, energy consumption is the lowest, because most modules of the system are closed except the clock and power management module.

In the proposed energy consumption model based on state transition, energy consumption is divided into two parts: a) state energy consumption ($E_s, s \in S_s$), i.e. energy consumption of each state; b) transition energy consumption ($E_t, c \in S_t$), i.e. energy consumption caused by state transition. Here, S_s is the collection of all the states of a module, S_t is the collection of all transition processes between these states, therefore, $S_t = \{t: m \rightarrow n, m, n \in S_s\}$. The process of state transition between different states is very short, but the energy loss during this process cannot be ignored. Thus, the energy consumption of a module can be calculated using the following equation:

$$E = E_s + E_t = P_s \times T_s + P_t \times T_t \quad (1)$$

where, P_s is the power of a module at a certain state; for a specific element, it is a constant. P_t is defined as the average value of the power under a transition process, namely

$$P_{t:m \rightarrow n} = (P_m + P_n) / 2 \quad (2)$$

where T_t is the duration of a certain state. $T_{t:m \rightarrow n}$ is the time of the transition process between two states. Therefore, the energy consumption of the entire node can be calculated using the following equation:

$$\begin{aligned} E &= \sum_{i \in S_s, j \in S_s} (E_i + E_j) = \\ &= \sum_{i \in S_s} P_i \times T_i + \sum_{j \in S_s} P_j \times T_j = \\ &= \sum_{i \in S_s} P_i \times T_i + \sum_{j=m \rightarrow n, j \in S_t} (P_m + P_n) / 2 \times T_{m \rightarrow n} \end{aligned} \quad (3)$$

where P_i , P_j and T_j are the constants. So the key for the calculation of the energy consumption of a node is to compute the duration T_i of a certain state.

The energy consumption model proposed in this paper is based on the dormancy method to reduce energy consumption. Because of the existence of energy consumption caused by state transition, there will be such a situation: energy consumption caused by frequent state transitions may be greater than that of a high energy consumption pattern. In this situation, transitions between each state are not feasible for the node; therefore, some constraints are required to be applied, namely time limitation [11]. To avoid the above mentioned situation, the authors adopt the following time limitation: if the energy consumption $E_{transmission}$ caused by frequent state transitions is smaller than that of the high energy consumption pattern, state transitions are allowed; otherwise, the high energy consumption pattern will be maintained. $E_{transmission}$ can be calculated using the following equation:

$$\begin{aligned} E_{transmission} &= E_{m \rightarrow n} + E_n + E_{n \rightarrow m} = \\ &= P_{m \rightarrow n} \times T_{m \rightarrow n} + P_n \times T_n + P_{n \rightarrow m} \times T_{n \rightarrow m} \end{aligned} \quad (4)$$

2.1.1. Work State Transition Model for Processors

The following switch conditions exist between the three states [12]:

- 1) Switching from running to sleep: when a task needs to process, the CPU is running; when there is no task or energy shortage, the operating

system may choose to enter the sleep state to save energy.

- 2) Switching from sleep to running: when an exception occurs, the CPU will be awakened to running state; the state switching period is very long, need to consume a lot of energy.
- 3) Switching from running to idle: in a certain time period, if the message queue is empty, the system will predict that no event occurs in recent time, and the processor will switch from running state to idle state.
- 4) Switching from idle to running: when a task needs to deal with, the idle state will be suspended and enter the running state.
- 5) Switching from idle to sleep: when the CPU is idle for a period of time with no event occurring, the CPU will be switched from idle state to sleep state.

2.1.2. Work State Transition Model for Communication Modules

Generally, the communication module consists of six states: TS, RS, OFF, Idle, Sleep, and CCA/ED. Each state is described as follows [13]:

TS: transmitting state. The communication module enters this state when sending packets.

RS: receiving state. The communication module enters this state when receiving packets.

OFF: off state.

Idle: idle state, waiting for the occurrence of events;

Sleep: sleep state, with low power consumption;

CCA/ED: clear channel assessment (CCA) and channel energy detection (ED).

After being triggered, the communication module will be switched from OFF state to idle state. At the idle state, the communication module will enter TS state to send data, enter RS state to receive data, or enter CCA/ED state to check the channel. When the CPU is idle for a period of time with no event occurring, the CPU will be switched from idle state to sleep state; when a task needs to deal with, the idle state will be suspended and enter the running state.

2.1.3. Work State Transition Model for Sensing Modules

The sensing module captures various related information through sensors, such as voltage, current, temperature, humidity, light intensity, pressure, etc. Then, the information captured will be transmitted to the processor module for integration and processing. Dissipative elements of the sensing module are converter, ADC, etc. Different tasks correspond to different working modes: sudden tasks require real-time data collection sensors, while periodic tasks only need periodic data collection sensors. In this work, the sensor module adopts the periodic mode,

namely the sensors are opening and closing periodically.

2.2. Overall and Module Energy Consumption Metastasis

Until now, energy consumption models for processor modules, communication modules, sensing modules have been established. The three models are separated; however, in practical applications, they are connected. Thus, we establish the connections between the three models based on event-triggered-mechanism, thereby establishing the overall node energy consumption model.

Both triggering events outside or inside the energy consumption models can result in state changes of each module. Triggering events outside the energy consumption models include clock cycle events and channel checking events; triggering events inside the energy consumption models include periodic data collection events, packet-transmitting events, and packet-receiving events [14]. Triggering events of each module are shown as following:

1) The sensor module of the clock cycle events becomes on state periodically, and returns off state after finishing energy consumption.

2) Periodic data collection events of sensing module energy consumption model will trigger the processor module energy consumption model. At this time, the processor will enter running state.

3) Sending packet events of processor module will trigger the communication module, and the communication module will be switched from idle state to TS state. Receiving packet events will make the communication module be switched from idle state to RS state. Channel checking events will make the communication module be switched from idle state to CCA/ED state.

If the clock cycle triggers the sensing module, the later will be switched from off state to on state, and the sensors will start data collection; the periodic data collection event will then trigger the processor module, namely the processor module will enter run state. If the transceiver receives packets, the communication module will be switched from idle state to RS state; meanwhile, the processor module will be activated.

Using the work state transition models for processor module, communication module, and sensing module, this work explores the energy consumption condition of each module at different working states. Then, energy consumption models are presented to reveal the energy variation laws of the energy-consuming elements. Last, based on event-triggering mechanism, an overall node energy consumption model is proposed. For a wireless sensor network system, using the overall node energy consumption model, each module will enter corresponding state according to the algorithm, to calculate the accurate energy consumption of each module and the overall node energy consumption.

3. Energy Consumption of Wireless Sensor Networks

The energy consumption conditions of processors SA-1200 and MSP420f159 are discussed. AODV protocol is adopted as the routing protocol of the node model in this work. System tasks include sending packets and the maintenance of the routing protocol. In the first 60 seconds, packet transmission interval is set to be 1 second; from the 60th to 140th second, set the interval as Poisson distribution with expectation of 11 seconds; after the 140th second, the interval is set to be 1 second. Simulation time is 250 seconds, wireless communication range is 250 meters, and the 15th node is taken to be analyzed.

3.1. Simulation Analysis

The simulation results are shown in Fig. 1 and Fig. 2. From the two figures we learn that, two curves have similar trends over time. The scaling laws are dependent on the tasks of the processor. Although the trends are similar, in the same task, energy consumption values are different. After 250 seconds, the energy consumption of processor SA-1200 is about 65J, while processor MSP420f159 is less than 0.3J. Therefore, processor MSP420f159 is more economic than processor SA-1200.

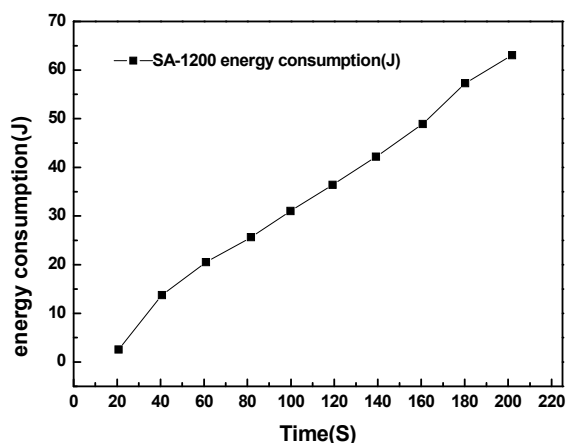


Fig. 1. Energy consumption of processor SA-1200.

Fig. 3 shows the energy consumption of processor SA-1200 at different working states. We learn that, energy consumption at running state is much greater than that at idle state, sleep state, and transition state. In practical applications, for different loads, power consumption curves are different, but the overall trend will not be changed. Since the energy consumption of the processor is very large at running state and very small at sleep state, thus improving sleep time and reducing running time are powerful means to reduce processor energy consumption.

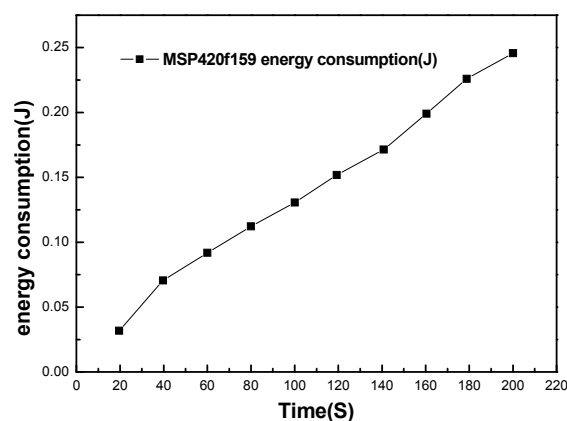


Fig. 2. Energy consumption of processor MSP420f159.

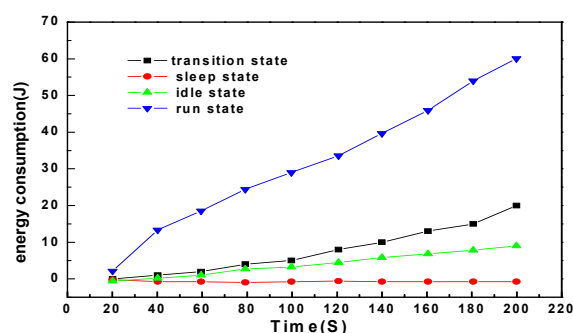


Fig. 3. Energy consumption of processor SA-1200 at different working states.

The energy consumption conditions of communication modules MC13213 and CC2420 are discussed. AODV protocol is adopted as the routing protocol of the node model in this work. System tasks include sending packets and the maintenance of the routing protocol. In the first 60 seconds, packet transmission interval is set to be 1 second; from the 60th to 140th second, set the interval as Poisson distribution with expectation of 11 seconds; after the 140th second, the interval is set to be 1 second. Simulation time is 250 seconds, wireless communication range is 250 meters, and the 16th node is taken to be analyzed.

The simulation results are shown in Fig. 4. The energy consumption of the two communication modules shows similar trends over time. However, communication module MC13213 is more economic than communication module CC2420. In this experiment, both the two selected communication modules are low power modules, so the energy consumption is small. Energy consumption of communication modules with high emission power and broad coverage will be considerably higher.

Fig. 5 shows the energy consumption curves of communication module CC2420 at different states. Due to the energy consumption curves of communication module CC2420 and MC13213 are similar; here only provide detailed description for the

energy consumption of module CC2420. We learn that, under the experimental load conditions of this work, energy consumption at RX state is much greater than the other states. In this wireless sensor network, a packet will be received by the communication module as long as it arrives within the communication range, and the node is to judge whether to accept or to discard. Therefore, the number of packets received by the communication module is larger than the number of packets transmitted.

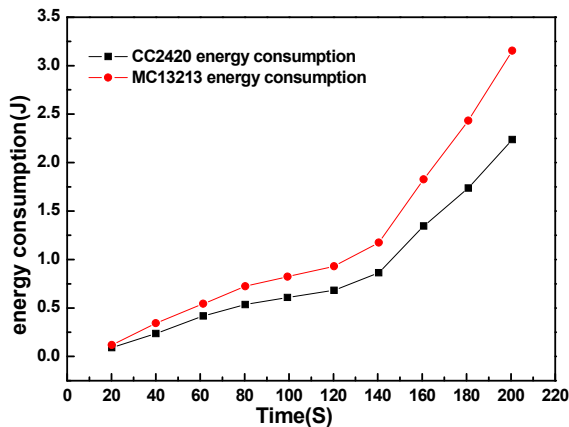


Fig. 4. Energy consumption of communication modules MC13213 and CC2420.

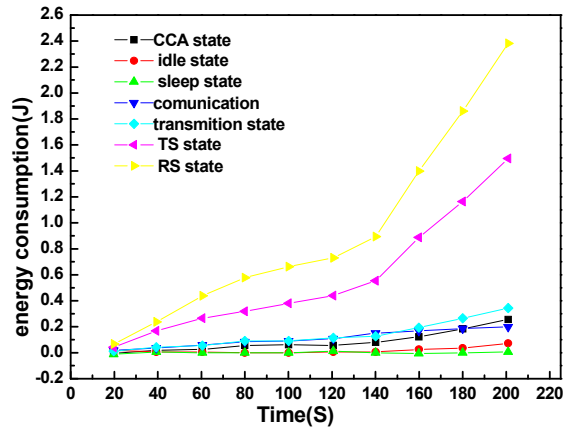


Fig. 5. Energy consumption curves of module CC2420 at different states.

Energy consumption conditions of the Communication module are similar at idle state, transition state, and the CCA state. Therefore, in the case of the application requirements of the wireless sensor network being guaranteed, to reduce the energy consumption of the communication module, the following measures shall be adopted: reducing communication traffic, reducing single-hop communication distance, using multi-hop short distance wireless communication, and keep the communication module be in sleep state.

This experiment examines the energy consumption of sensing module under different working cycles, here sensing period T is taken as 10 seconds and 20 seconds respectively. AODV protocol is adopted as the routing protocol of the node model in this work. In the first 60 seconds, packet transmission interval is set to be 1 second; from the 60th to 140th second, set the interval as Poisson distribution with expectation of 11 seconds; after the 140th second, the interval is set to be 1 second. Simulation time is 250 seconds, wireless communication range is 250 meters, and the 7th node is taken to be analyzed.

Fig. 6 shows the energy consumption curves of the sensing model when sensing period is 10 and 20 seconds. The energy consumption curves of the sensing model are approximate linear lines. The slope of the energy consumption curve with 10 s sensing period is twice of the energy consumption curve with 20 s sensing period, indicating that energy consumption is inversely proportional to the sensing period, and is not subjected to the impact of other factors.

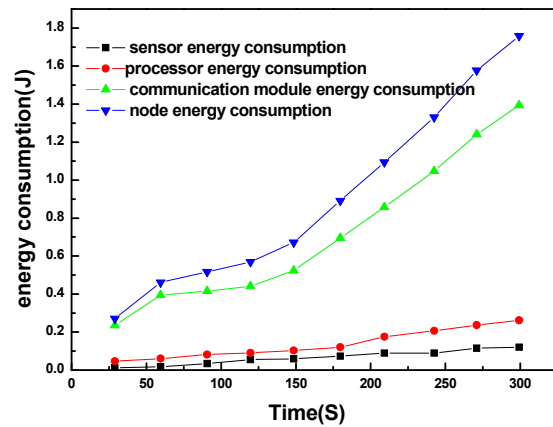


Fig. 6. Energy consumption curves of the sensing module.

3.2. Simulation Results and Analysis for Overall Node Energy Consumption

This experiment analyzes the effects of processor module, communication module, and sensing module on the overall energy consumption of nodes. Processor MNP430f 249, communication module CC2420 and temperature sensor DA18B30 (sensing period $T=10$ s) are selected in this work. This model contains 20 nodes in the range of 1000×500 . DSR protocol is adopted as the routing protocol of the node model in this work. In the first 60 seconds, packet transmission interval is set to be 3 second; from the 60th to 140th second, set the interval as Poisson distribution with expectation of 11 seconds; after the 140th second, the interval is set to be 1 second. Simulation time is 250 seconds, wireless communication range is 250 meters, and the 8th node is taken to be analyzed.

Fig. 7 shows the energy consumption conditions of each module and the overall node energy consumption. As can be seen, the energy consumption of the sensing module is the lowest, and the energy consumption of the communication module is the largest. Therefore, the communication module contributes most of the energy consumption of the node. However, in certain situation (such as image processing, etc.), the energy consumption of the processor module is equals to that of the communication module. To solve this problem, measures such as dynamic voltage regulator and dynamic power management can be adopted to reduce the energy consumption of the processor module.

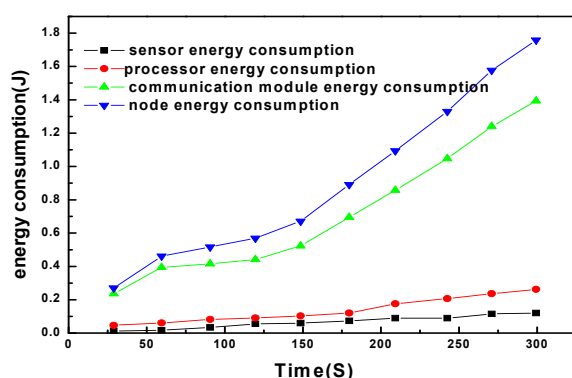


Fig. 7. Energy consumption curves of the DSR protocol.

4. Conclusions

This paper compares the energy consumption of processor SA-1200 and MSP420f159, revealing that processor MSP420f159 is more energy-efficient. Both communication module MC13213 and CC2420 are low energy-consumption modules, and the scaling law of sensing period and energy consumption is verified. Energy consumption of the processor and the communication module at different states is studied; indicating the key factors affecting the energy consumption of the processor is the running state, while the key factor for the communication module is the RS and TS state. For the whole node, the communication module contributes most of the energy consumption. This paper presents an overall node energy consumption model to analyze the energy consumption of the processor module, communication module, and the sensing module under different states. Using this model, each module can select to enter different operating states depending on loads, achieving the load-dependent mode. The article also has some shortcomings, such as the neglect of the effect of energy supply modules, which require further works to be implemented.

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References

- [1]. G. Anastasi, M. Conti, M. Di Francesco, A. Passarella, Energy conservation in wireless sensor networks: A survey, *Ad Hoc Networks*, Vol. 7, Issue 3, 2009, pp. 537-568.
- [2]. N. Aslam, W. Phillips, W. Robertson, S. Sivakumar, A multi-criterion optimization technique for energy efficient cluster formation in wireless sensor networks, *Information Fusion*, Vol. 12, Issue 3, 2011, pp. 202-212.
- [3]. J. W. Branch, C. Giannella, B. Szymanski, R. Wolff, H. Kargupta, In-network outlier detection in wireless sensor networks, *Knowledge and Information Systems*, Vol. 34, Issue 1, 2013, pp. 23-54.
- [4]. M. C. M. Thein, T. Thein, An energy efficient cluster-head selection for wireless sensor networks, in *Proceedings of the IEEE International Conference on Intelligent Systems, Modelling and Simulation (ISMS'2010)*, 2010, pp. 287-291.
- [5]. A. Bachir, M. Dohler, T. Watteyne, K. K. Leung, MAC essentials for wireless sensor networks, *IEEE Communications Surveys & Tutorials*, Vol. 12, Issue 2, 2010, pp. 222-248.
- [6]. J. Ma, W. Lou, Y. Wu, X. Y. Li, G. Chen, Energy efficient TDMA sleep scheduling in wireless sensor networks, in *Proceedings of the IEEE International Conference (INFOCOM'09)*, 2009, pp. 630-638.
- [7]. M. Ceriotti, L. Mottola, G. P. Picco, A. L. Murphy, S. Guna, M. Corra, P. Zanon, Monitoring heritage buildings with wireless sensor networks: The Torre Aquila deployment, in *Proceedings of the IEEE International Conference on Information Processing in Sensor Networks*, 2009, pp. 277-288.
- [8]. D. Parabola, S. Okdem, C. Ozturk, Cluster based wireless sensor network routing using artificial bee colony algorithm, *Wireless Networks*, Vol. 18, Issue 7, 2012, pp. 847-860.
- [9]. F. Viani, P. Rocca, G. Oliveri, D. Trincherio, A. Massa, Localization, tracking, and imaging of targets in wireless sensor networks: An invited review, *Radio Science*, Vol. 46, Issue 5, 2011, Article ID. RS5002.
- [10]. M. Di Francesco, S. K. Das, G. Anastasi, Data collection in wireless sensor networks with mobile elements: A survey, *ACM Transactions on Sensor Networks*, Vol. 8, Issue 1, 2011, Article No. 7.
- [11]. S. Chouhan, R. Bose, M. Balakrishnan, A framework for energy-consumption-based design space exploration for wireless sensor nodes, *IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems*, Vol. 28, Issue 7, 2009, pp. 1017-1024.
- [12]. B. Yahya, J. Ben-Othman, Energy efficient and QoS aware medium access control for wireless sensor networks, *Concurrency and Computation: Practice and Experience*, Vol. 22, Issue 10, 2010, pp. 1252-1266.

- [13]. J. Jia, J. Chen, G. Chang, Z. Tan, Energy efficient coverage control in wireless sensor networks based on multi-objective genetic algorithm, *Computers & Mathematics with Applications*, Vol. 57, Issue 11, 2009, pp. 1756-1766.
- [14]. V. Sharma, U. Mukherji, V. Joseph, S. Gupta, Optimal energy management policies for energy harvesting sensor nodes, *IEEE Transactions on Wireless Communications*, Vol. 9, Issue 4, 2010, pp. 1326-1336.

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