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에너지 효율적인 무선 센서 네트워크를 위한 통신 이벤트 기반의 전력 관리 방안에 관한 연구

종신회원 황 광 일*

Communication Event-driven Power Management for Energy Efficient Wireless Sensor Network

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요 약

무선 센서 네트워크에서 가장 큰 문제 중의 한 가지는 네트워크를 구성함에 있어 에너지 소모를 최소화하는 데 있다. 센서 네트워크에서 에너지를 효율적으로 사용하기 위해서 주로 다음과 같은 두 종류의 방식을 사용한다. 한 가지는 동적 전력 관리를 사용하는 것이며, 다른 한 가지는 에너지 효율적인 프로토콜을 사용하는 것이다. 전자의 경우 전원 관리자는 해당하는 이벤트들에 대해서 CPU와 해당 I/O들의 적절한 전원 상태를 관리할 책임이 있다. 하지만, 주어진 프로토콜의 내부 동작에 대해서는 관여 하지 못한다. 그것은 충돌 등으로 인한 통신 상태에서의 지연에 의한 불필요한 에너지를 낭비할 가능성이 크다. 반면에 에너지 효율적인 프로토콜들은 단지 무선 모뎀의 전원 상태만을 고려한다. 본 논문에서 우리는 통신 이벤트 기반의 전력 관리를 통한 무선 센서 노드들의 불필요한 전력 소비를 충분히 줄일 수 있는 에너지 효율적인 전력 관리 방안을 제안하고, 시뮬레이션을 통해 제안하는 전력 관리 방식이 상당한 에너지를 절약 할 수 있음을 보인다.

Key Words : Energy-efficiency, MAC, Network protocol, Power management, Wireless sensor networks

ABSTRACT

It is well known that the biggest problem of wireless sensor networks is power conservation. There have been two major approaches to efficiently use energy in wireless sensor networks. One is to use a dynamic power management scheme and the other is to use energy efficient protocols. In the former, the power manager is responsible for managing the proper power state of CPU and each I/O with respect to the events, but the power manager does not concern about the internal operation of the underlying network protocols. Thus such conventional power managers can waste unpredicted power during communication period. On the other hand, the energy efficient protocols are just focused on the power saving operation of the radio PHY. In this paper, we introduce an energy-efficient power saving mechanism that can significantly reduce unwanted power consumption of wireless sensor nodes through the communication event-driven power management. We show that our scheme improves the energy conservation in the entire network through simulations.

Ⅰ. Introduction

Advances in wireless communications and electronics in recent yearshave enabled the development of low-cost, low-power and small-size wireless sensor nodes. There exist obvious

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differences[19] between the wireless nodes of wireless sensor networks and the wireless nodes of traditional wireless networks. The former has much severer constraints on energy, computation power, storage, and bandwidth than the latter. The biggest problem of wireless sensor networks operated with battery is how to conserve energyefficiently since they are normally expected to operate very long time without battery replacement or recharge. Power conservation is much more important in wireless sensor networks. This is because they are normally expected to operate without user management due to their inaccessible operation environment and the cost for battery replacement or recharge is too expensive due to the great many number of nodes consisting of a wireless sensor network. This means that the battery replacement or recharge is impossible or very expensive in wireless sensor network unlike the traditional wireless networks where the users easily recharge or replace the batteries of wireless nodes such as cell phones or notebook computers. In addition, the battery capacity of wireless sensor nodes is restricted due to their size limitation.

The unique features of wireless sensor networks also require the design of very compact sensor node. Fig. 1 shows a typical architecture of a wireless sensor node[19]. As shown in Fig. 1, a wireless sensor node consists of four major parts Processor unit, Memory unit, wireless PHY, and Sensing unit. Each unit is fed by a central power generator, battery, and shares address, data, and control buses. Also, each unit should havethe ability for power saving, that is, they have the power saving modes such as IDLE, PWDN etc. The power management is implemented by managing the power modes.

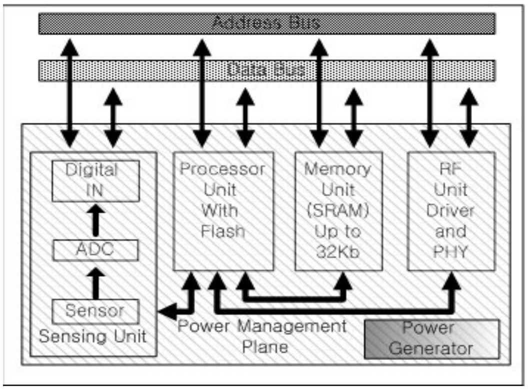


Fig. 1. Architecture of Wireless Sensor Node

To efficiently use energy in wireless sensor networks, a number of methods have been proposed. They are largely classified into two approaches; event-driven power management methods[1-11] and energy efficient protocols such as IEEE 802.11[13], EC-MAC[14], and PAMAS[15]. In the event-driven power management methods, the power manageris responsible for managing the proper power state of CPU and each I/O with respect to the events but the power manager doesnot concern about the internal operation of communication protocols. On the other hand, the energy efficient protocols are just focused on the power saving operation of the radio PHY. We note that two approaches can be efficiently combined in wireless sensor networks to which the layering concept of network protocols is not strictly applied.

In this paper, we introduce a novel power saving mechanism which can save energy significantly by considering the events related to the underlying network protocol appropriately. Through performance analysis, we show that the proposed power management scheme is more efficient than the conventional power management schemes in wireless sensor networks, in terms of energy efficiency.

Ⅱ. Two Approaches For Energy Conservation

In this Section, we examine two approaches to efficiently use finite energy; dynamicpower management methods and energy efficient protocols. Although those approaches can achieve a satisfying result in typical wireless networks, wireless sensor networks having much severer restriction on energy conservation require more efficient power saving scheme.

2.1 Dynamic Power Management

Dynamic power management (DPM) schemes use runtime behavior to reduce power when systems are idle[1-2]. They are basically an event-driven power management where the power state of the system is determined by the state of the event queue. If there is no task in the event queue, the system goes to the idle state until a new task occurs. Such method is simple enough to be implemented in a wireless sensor node, and useful especially for the nodes with a small number of I/O devices.

Time-out policy[3] can be described as follows. For an idle period to start, a counter with an appropriate timeout value is established. If the system is still idle after timeout, then the power manger forces the transition to the off (idle) state. The system remains off until it receives a request from the interrupts that signals the end of the idle period. But, the policy has the drawback that power is wasted while waiting for the counter to expire. Therefore, adaptive timeout policies have been proposed in [4-5]. In the adaptive timeout, a set of timeout values is maintained and each timeout is associated with an index indicating how successful it would have been. However, the above predictive policies are heuristic and involve not only the choice of when to perform state transitions but also the choice of which transition should be performed.

In [6-7], the arrival of requests and device power-states can be modeled as a stochastic process. A simple stochastic policy for the request and power-state transitions are modeled as a stationary discrete-time parameter Markov chain[6] or a continuous-time parameter Markov chain including non-stationary behavior[7]. However, the stochastic policy implementation in practice may not be simple.

2.2 Energy Efficient Protocols

Of the protocols in the protocol stack, MAC protocol which is responsible for managing the multiple accesses for a common channel and operating PHY is especially important from the viewpoint of energy. Several energy efficient MAC protocols[13-16] have been proposedfor wireless networks. There are a variety of multiple access methods such as TDMA, FDMA, and CSMA. The CSMA-based MAC protocols are widely used for wireless sensor networks since an Ad-hoc basis operation is required in wireless sensor networks without infrastructure[9]. However, in the CSMA-based MAC protocols, a large amount of energy is wasted when collisions occur during the channel access. If a node loses chance for the communication due to collision, it should wait for until the channel is free. Therefore, in the energy efficient MAC, the state of the PHY should be changed into an idle state or turning it off during such adefer access period.

The EC-MAC (Energy Conserving-MAC)[14] protocol is used for a wireless network with infrastructure where a single base station serves the mobiles in its coverage area. It can be extended to an ad hoc network by allowing the mobiles to elect a coordinator to perform the functions of the base station. However, since the major object of the protocol is to support QoS with reservation and scheduling strategies, it is not suited for wireless sensor networks. While the EC-MAC protocol was designed primarily for infrastructure wireless networks, the PAMAS (Power Aware Multi-Access)[15] was designed for ad hoc wireless networks. The PAMAS protocol modifies the MACA(Karn, 1990) protocol by providing separate channels for the RTS/CTS control packets. Power conservation is achieved by requiring the mobiles that are not able to receive and send packets to turn off their wireless interfaces.The two separate physical channels for control packets and data packets come to overheads for the hardware of a wireless sensor node.

The IEEE 802.11 MAC[13] supports two power modes; the active mode and the power saving (PS) mode. When a node stays in the PS mode, it wakes up periodically. When the network

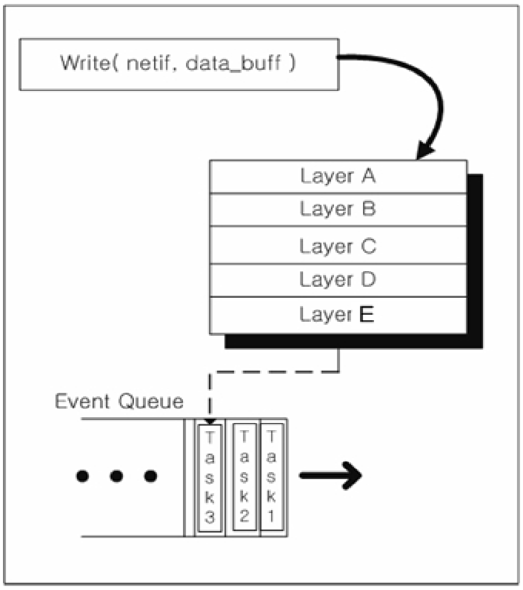


Fig. 2. Example of DPM with Network Data

is operated in the ad hoc mode, the short interval where the nodes in the PS mode wake up is called the ATIM window. Currently, many of wireless sensor networks are adopting this CSMA-based MAC protocol.

So far, we have briefly introduced two approaches proposed to efficiently use energy for wireless sensor networks. In the dynamic power management schemes, the power manager is responsible for managing the proper power state of CPU and each I/O with respect to the events. However,the power manager does not concern about the internal operation of each protocol although most of the tasks in wireless sensor nodes depend oncommunication-based events. Even sensing tasks are not independent on but connected with the underlying network.

Therefore, an event-driven power management scheme considering the situations happened by theunderlying communication protocols become necessary in wireless sensor networks. For example, we consider following situation. If the system has the data to be sent, its OS put the network task into the event queue as shown in Fig. 2. However, when congestion or collision occurs in the network, the Task3 related to data communication should be delayed until the problem is solved. Therefore, in spite of doing nothing until the Task3 is completely finished, CPU should be in the active state. Since hundreds to thousands of nodes are densely deployed in a wireless sensor network, such blockings occur frequently and thus lead significant energy waste.

Even if the dynamic power management scheme is used with the energy efficient protocols, the above mentioned energy waste still occurs. This is so because all the protocols are designed based on the layering concept whether they are on the data plane or the control plane. That is, the internal operation of a protocol is invisible to the other protocols.

In general, such a layering concept gives the flexibility to design each protocol independently, and it thus can save the time and effort needed to design the protocols. In addition, it gives us the design modularity since any two adjacent protocols in the protocol stack can be easily interfaced. Although the layering concept gives many advantages in terms of design efficiency, it is well known that it wastes considerable resources such as memory, processing power. Therefore, the layering concept is not strictly applied to wireless sensor networks with resource limitation. Instead, the protocols are tightly coupled to save resources. The proposed power management scheme uses this property of wireless sensor networks, as will be explained in the next Section.

Ⅲ. Communication Event-Driven Power Management

In Section 2, we have explained that the conventional dynamic power management schemes are not well suited for wireless sensor networks even if they are used with the energy efficient protocols. Therefore, we propose a new power management scheme for wireless sensor nodes which have much severer constraints on energy, computationpower, storage, and bandwidth than the traditional wireless nodes. We call the

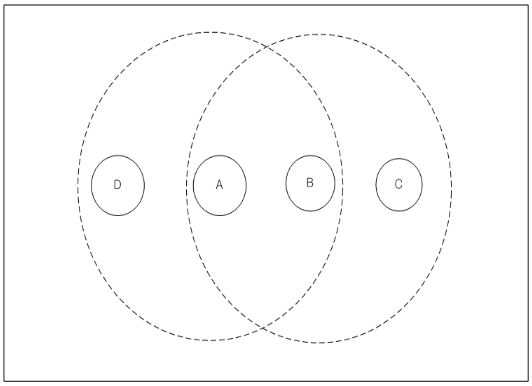


Fig. 3. simple contention-based network architecture

proposed power management scheme CEPM (Communication Event-driven Power Management). Its main idea is to maintain network event-based queue for power management of a node. Especially, a MAC protocol-based event queue is maintained since MAC protocol is responsible for managing the multiple accesses for a commonchannel and operating PHY. Although our power management scheme is independently operated in each node, energy conservation in the entire network is naturally achieved because the power management is operated based on the network events.

3.1 Mechanisms of CEPM

CEPM is differentiated from others in that it manages the states of all the I/O devices by using the events happening in the MAC protocol.

To help understanding the operation of CEPM, suppose that there are four sensor nodes in thewireless sensor network as shown in Fig. 3. The nodes use a CSMA-based MAC protocol with the contention windows, the RTS/CTS control frames, and the back-off algorithm. We assume that node A wants to send data to node B. It first sends an RTS frame to node B to request permission to send its data. When node B receives this request, it may decide to grant permission, in which case it sends a CTS frame back. On receipt of the CTS, node A sends its data and starts an ACK number. On correct receipt of the data, node B responds with an ACK, and then terminates the exchange. From the information provided by the RTS request, node Dcan estimate how long the sequence including the final ACK will take,

it thus asserts a kind of virtual channel busy for itself, which is indicated by the NAV (Network Allocation Vector) in Fig. 4. Node C cannot hear the RTS from node A, but it can

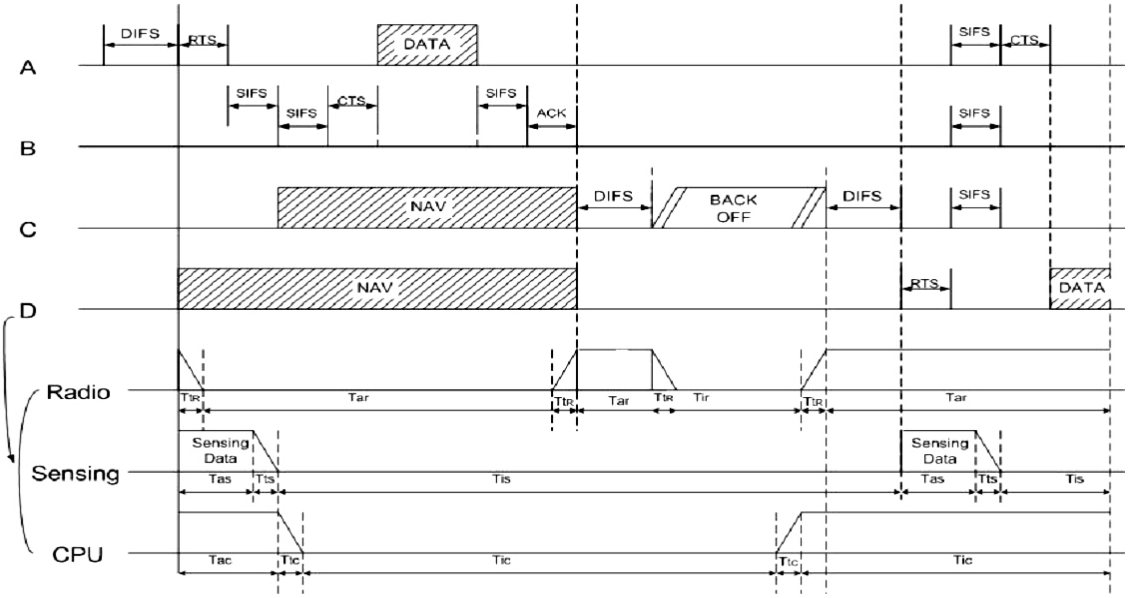


Fig. 4. Operation of CEPM on the CSMA-based MAC

hear the CTS from node B, so it also asserts the NAV to keep quiet for an appropriate period of time. Node D listens the RTS from node A.

On the other hand, the sensing unit in node D repeating periodic sleeping and sensing awakes to sense some kind of physical phenomenon. Then, node D should send the sensing data into the other corresponding actuator or sink through node A. However, since the network is blocked by node A that is sending data, node D should wait after putting the data into a queue, until the transmission of node A is over. Here, in the traditional event-driven power management schemes, although there is no operation during the blocking time, the CPU state of node D is not transited into the idle state since the data still remains in the queue.

However, CEPM considers all the state of I/O devices such as Radio, Sensing, and CPU by using the events related to the MAC internal operation, as shown in Fig. 3. In CEPM, the CPU state of node D can be in the idle state during collision time, since it is dependent on the MAC operation. Especially, for a wireless sensor network where numerous nodes are deployed within the radio range, CEPM can efficiently save energy by letting the power modes of CPU and Radio be more frequently in the idle state, since the above mentioned blocking occurs frequently in such a network. It is obvious that the difference of CPU power consumption between the active state and the idle state is significant. For example, in AT89LV52of ATMEL inc., CPU consumes 21.45mW in the idle state while it consumes 81.5mW in the active state.

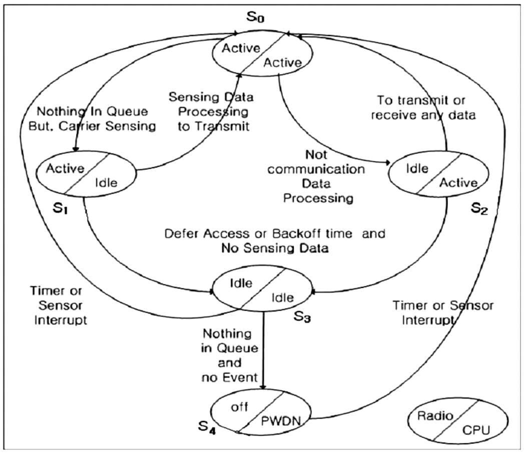


Fig. 5. Transition Diagram between states in a wireless node

Figure 5 shows the state transition diagram for the power modes of CPU and Radio. Each state transits into other states when the following conditions are satisfied. Firstly, the events related to the communication occur or the event queue is empty. Secondly, the timer is invoked (i.e., the NAV timer). Finally, the external interrupts areinvoked (i.e., sensor data over threshold). In the listening periods, the state of a node is in S1. If sensing data should be transmitted, the state goes to S0. When there are the tasks not to communicate but to process, the state goes to S2. When the data to be sent is blocked, the state should go to S3. If nothing happens for a long time or energy of the node is almost being depleted, the state goes to S4.

3.2 Analysis of CEPM

We can calculate the total energy consumed in a node by summing up the energy consumed in each unit of the node, for all the states. Therefore, the total energy is expressed as follows;

$$E = \sum_{i=0}^{3} Power_{Si} \times \int_{start\_time\ of\ Si}^{end\_time\ of\ Si} tdt \qquad (1)$$

where $Power_{Si}$ is the sum of power consumption of each unit for the state i. Since the value of $Power_{Si}$ is hardware-specific constant, energy efficiency can be analyzed by just considering the holding time of each state.

We consider a stochastic process $\{X_n, n = 0,1,2...\}$ that takes on a finite or countable number of possible values. If $X_n = i$, then the process is said to be in state i at time n. We suppose that

$$P\{X_n = j \mid X_{n-1} = i_{n-1}, ...X_0 = i_0\} = P\{X_n = j \mid X_{n-1} = i_{n-1}\}$$

(for all $n \geq 0$) (2)

That is, a Markov chain is assumed.

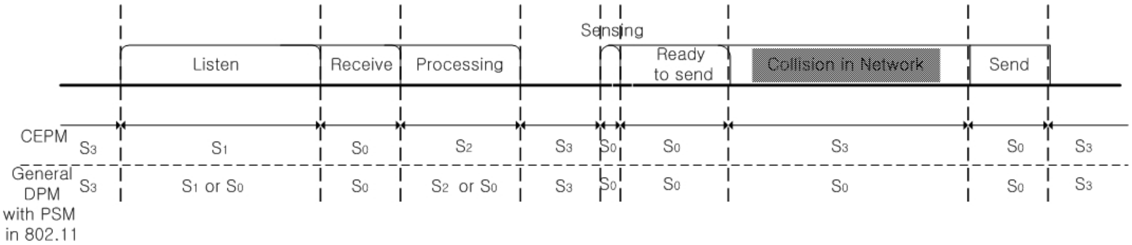


Fig. 6. State Transition Abstraction for Wireless Sensor Networks

$$P\{X_n = j \mid X_{n-1} = i\} = P_{Si,Sj}) \qquad (3)$$

Note that the proposed power management scheme CEPM can be modeled by a Markov Chain since the next state depends on only the current state as shown in Fig. 5. Each state is defined in Table 1. Since sensing unit wakes up and senses a physical phenomenon periodically, the state holding time of the sensor unit is constant. Thus, we do not consider the state of sensing unit.

We can analyze the energy efficiency of CEPM by obtaining the limiting probability distribution $\{\pi_{sj} = \lim_{m\to\infty} p^{(m)}_{si,sj}\}$ of the Markov chain since π_{sj} is directly proportional to the holding time of state S_j. However, by considering the state variations of the power management schemes in a general communication situation as shown in Fig. 6, we can roughly compare the energy efficiencies of CEPM and the traditional power management schemes without obtaining the limiting probability distributions. This approach is useful since it is difficult to strictly analyze the energy efficiencies of other power management schemes.

Table 1. Description of each Power State

State	Description
S0	CPU unit Active and Radio Active
S1	CPU unit idle and Radio Active
S2	CPU unit Active and Radio Idle
S3	CPU unit Idle and Radio Idle

Table 2. Comparison of π_{S_j}

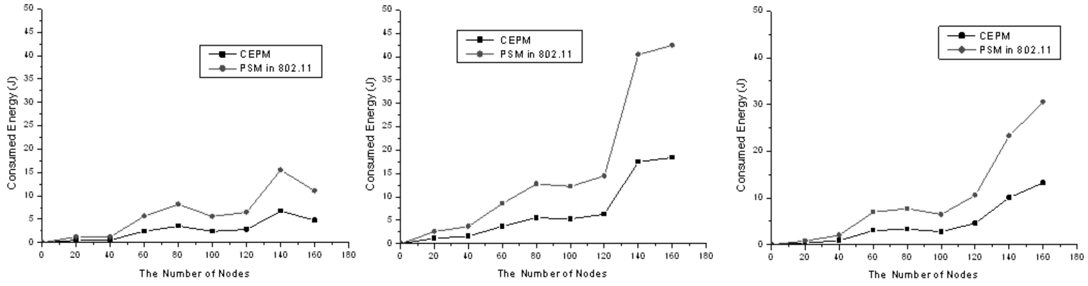
π_{S_j}	CEPM vs. Non CEPM
π_{S_0}	CEPM 〈 Non CEPM
π_{S_1}	CEPM ≥ Non CEPM
π_{S_2}	CEPM ≥ Non CEPM
π_{S_3}	CEPM 〉 Non CEPM

But since most of processes of a wireless sensor network can be abstracted as shown in Fig 6, we can thus compare π_{S_j} of the power management schemes which are directly proportional to the frequency of entering the corresponding state, relatively. Table 2 shows the comparison result for the state holding time. It is obvious that the state holding of S_0 is shorter and the state holding time of S_3 is longer in CEPM than in the traditional power management scheme (i.e., non CEPM).

Therefore, CEPM has more energy efficiency than the traditional power management scheme with an energy efficient protocol. That is, by letting the state of a wireless sensor node be more in the idle state, CEPM can save energy more efficiently.

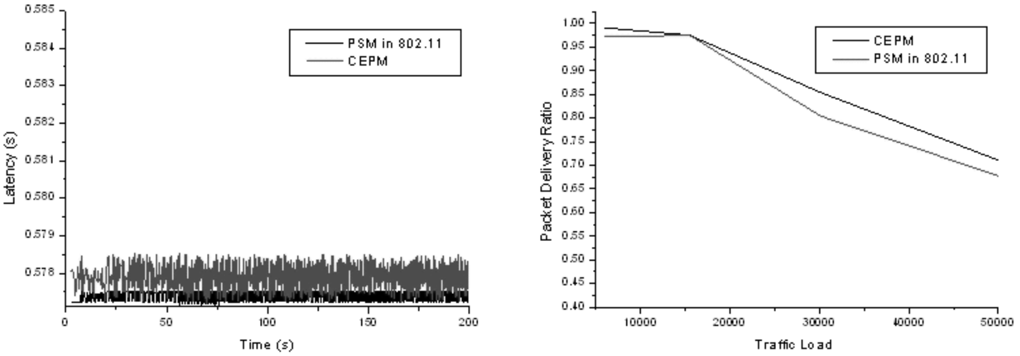
Ⅳ. Performance Evaluations

We used ns-2[18] for the performance evaluation of the proposed CEPM by simulation. It was implemented by embedding a MAC event-driven power manager in each mobile node.



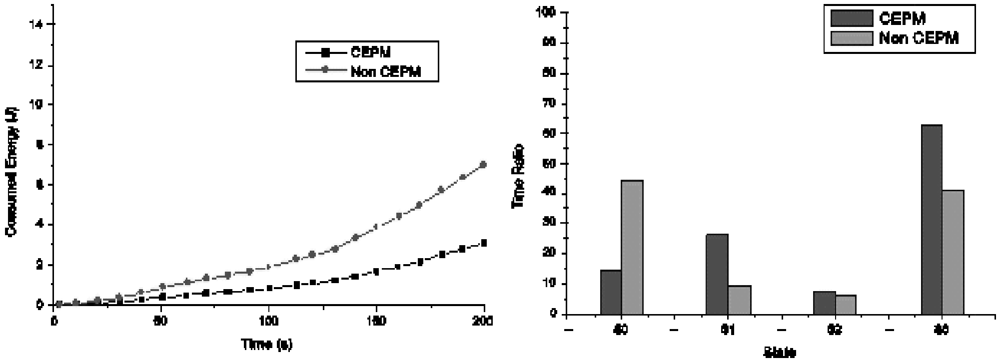
(a) Data Source Node (b) Intermediate (Relay) Node (c) Sink Node

Fig. 7. Consumed Energy vs. increment of the number of node, Data source node, Intermediate node, and Sink node, respectively



(a) Delay (b) Packet Delivery Ratio

Fig. 8. Comparison of Delay and Packet Delivery Ratio; CEPM and Power Saving mode in 802.11



(a) Overall Consumed Energy (b) Time ratio at each state

Fig. 9. Overall Energy Consumption with respect to time

Table 3. power consumption for each unit

Unit	Active	Idle
Radio (Tx)	0.4mW	0.1mW
(Rx)	0.05mW	0.1mW
CPU	1.5mW	0.65mW

For all the simulations in this Section, we compared the proposed CEPM with the power saving mode of IEEE 802.11.

In our simulation, each time-step, each sensor node can be in one of the states describedin Table 1 and it consumes energy according to its state. The power consumption of each unit is described in Table 3.Table 3: power consumption for each unit

For our simulations, we assume that AODV on-demand routing protocol is used for routing and thesource node transmits data packets with 512 bytes at 1Mbps speed.

4.1 Metrics

We employ four metrics for the performance evaluation of CEPM.

Energy consumption of each node measures cumulatively consumed energy in the source node, the intermediate (relay) node, and the sink node, respectively, with respect to increment of the number of nodes. That is used to evaluate which node consumes more energy.

Delay and Packet delivery ratio are very important performance metrics in traditional wireless networks, but in wireless sensor networks having significant energy restriction, the two metrics are considered as secondary problem. We examine how much energy can be conserved with CEPM while letting the delay and packet delivery ratio minimized.

Overall energy consumption is the average total consumed energy in the network. It is used to show how much the proposed CEPM affects energy conservation in the entire network.

4.2 Simulation Results

Figure 7 shows the simulation results about the cumulatively consumed energy in the source node, the relay node, and the sink node with respect to increment of the number of total nodes. The energy consumption of the source node is less sensitive to the increment of the nodes in the network. However, the sink node consumes more energy as the number of nodes increases. It comes from the fact that more data flows into the sink node as the number of nodes increases so that the sink node should stay more frequently in the receive mode. The reason why the energy consumption of the relay node is higher than other nodes is as follows. As the number of nodes increases, more data packets are transmitted from the source nodes, and thus the relay nodes deliver data packets to the sink node more frequently through the multi-hop routes.

That leads lasting of wake-up state as well as many of collisions and congestions. Therefore, more energy is consumed in the relay nodes. However, as shown in Fig. 7 (b), the proposedCEPM can cope with such situations by driving the proper power state related to the current network event. Overall, the results of Fig. 7 show that the proposed CEPM outperforms the power saving mode of IEEE 802.11.

Figure 8 shows the simulation results about the delay variation and the packet delivery ratio. We can see that the proposed CEPM results in the increases in the delay and the packet loss. It is because the change of power mode requires a processing delay and the proposed CEPM enters the power saving states more frequently to save energy. That is, the proposed CEPM achieves energy efficiency at the expense of the increases in the delay and the packet loss. However, such increases are not very much, and the delay and the packet loss are considered as secondary problem in wireless sensor networks having significant energy restriction.

Figure 9 shows the average total energy consumption of the wireless sensor network with respect to time. As explained previously, although the proposed CEPM is independently operated in each node, the energy conservation in the entire network is naturally achieved because it is operated based on the network events.

Ⅴ. Conclusion

The traditional power management schemes are not well suited forwireless sensor networks since they do not concern about the internal operations of the underlying communication protocols, although most of the tasks are dependent on the network events. Therefore, we have proposed a new power management scheme to reduce unwanted power consumption of wireless sensor nodes through the communication event-driven power management. We have shown that the proposed CEPM outperforms the power saving mode of IEEE 802.11 on the whole, through the simulations. In addition, we have shown that the energy conservation in the entire network can be achieved although the proposed CEPM is independently operated in each node.

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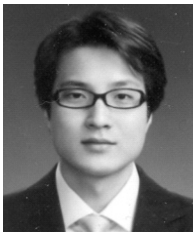

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