An Energy Efficient MAC Protocol Providing Guaranteed Service for Wireless Sensor Network

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Abstract

In this paper, we propose an Energy Efficient Media Access Control (EE-MAC) protocol for wireless sensor networks. The proposed scheme is designed to save power consumption and guarantee quality-of-service for real-time traffic. EE-MAC uses the superframe structure which is bounded by the transmission of a beacon frame and can have an active and an inactive portion. The active period is divided into the contention free period (CFP) for real-time traffic transmission and the contention access period (CAP) for non-real-time traffic transmission. We propose the exclusively allocated backoff scheme which assigns a unique backoff time value to each real-time node based on bandwidth allocation and admission control. This scheme can avoid collision between real-time nodes by controlling distributed fashion and take effect a statistical time division multiple access. We also propose the algorithm to change the duty cycle adaptively according to channel utilization of media depending on network traffic load. This algorithm can prolong network lifetime by reducing the amount of energy wasted on idle listening.

Keywords: WSN, MAC, energy efficient, guaranteed service

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1. Introduction

Wireless sensor networks have drawn much attention as efficient applications for environmental monitoring, medical care, remote robot exploring, and so on [1]. These kinds of networks take pattern of multi-hop networks of distributed nodes. Each node, usually activated by battery, has multiple sensors, an embedded processor, and low-power radio components. Typically, these nodes work cooperatively to perform some common processes among them.

In all wireless networks, nodes must share a single medium for communication. Network performance largely depends upon how efficiently the nodes can share this common medium.

In the literature, there are many proposals for MAC schemes to save power consumption and to provide guaranteed service in WSNs. Here, we are not going to survey these applications as the information can be found in [2][3][4][5]. Nevertheless, in the following, we still review some typical proposals before introducing our proposal.

S-MAC [3] was proposed to save energy consumption. The basic idea of this single-frequency contention based protocol is that time is divided into fairly large frames. Every frame has two parts: an active part and a sleeping part. During the sleeping part, a node turns off its radio to preserve energy. During the active part, it can communicate with its neighbors and send any messages queued during the sleeping part. In S-MAC protocol, communication latency may increase since every node sleeps periodically. However, S-MAC saves energy efficiently by reducing the energy wasted on idle listening. Adaptive S-MAC [6] was proposed, called *adaptive listen*, to improve the latency caused by the periodic sleep of each node in a multi-hop network. The basic idea is to let the node who overhears its neighbor's transmissions (ideally only RTS or CTS) wake up for a short period of time at the end of the transmission. In this way, if the node is the next-hop node, its neighbor is able to immediately pass the data to it instead of waiting for its scheduled listen time. If the node does not receive anything during the adaptive listening, it will go back to sleep until its next scheduled listen time. However, these schemes increase node complexity to operate adaptively.

Because S-MAC and adaptive S-MAC mainly focus on reducing energy consumption caused by idle-listening or overhearing, they cannot provide guaranteed services for real-time applications.

Z-MAC [5] is a hybrid MAC that uses CSMA as the baseline MAC scheme, but uses a TDMA schedule as a hint to enhance contention resolution. Like CSMA, Z-MAC achieves high channel utilization and low latency under low contention and like TDMA, achieves high channel utilization under high contention and reduces collision among two-hop neighbors. But Z-MAC does not consider energy consumption to enhance channel utilization and latency.

Recently, IEEE has announced a standard for wireless personal area network, IEEE 802.15.4 [7][8], which is adopted as ZigBee specification [9]. The characteristics of this standard are as follows: A personal area network (PAN) operates either in beacon mode or non-beacon mode. In beacon mode, a node selected as the PAN coordinator (PNC) transmits beacon signal periodically for synchronization. Also, PAN has a superframe structure which consists of active part and inactive part. The active part is divided into CAP and CFP. PAN works as slotted CSMA/CA during CAP and provide guaranteed time slot (GTS) service by operating like TDMA during CFP. During the inactive period, every node can sleep by turning off its radio to preserve energy like S-MAC. However, this protocol may not be efficient in terms of energy consumption compared with Adaptive S-MAC, and it is very complex to make allocation, release, and reallocation of GTS for real-time traffic.

In this paper, we propose EE-MAC protocol for wireless sensor networks which has the power saving features to prolong network lifetime and can provide guaranteed service. To save power consumption, the *adaptive adjusting duty cycle scheme* is devised. Also, to provide simple guaranteed service, *the method of allocating an exclusive unique backoff time value to each real-time node (rt-node)* is devised. This method cooperates with the admission control and bandwidth allocation method.

In Section 2, we discuss the complexity of GTS managing scheme of IEEE802.15.4 standard. Section 3 describes the design issues on our protocol including the adaptive adjusting duty cycle scheme and the exclusive allocated backoff scheme. The performance evaluation of energy consumption and delay is given in Section 4. Section 5 concludes the paper.

2. GTS Managing Scheme of IEEE802.15.4

To request the allocation of a new GTS, the device shall send the GTS allocation request command to the PNC. The PNC shall confirm its receipt by sending an acknowledgment frame. On receipt of a GTS allocation request command, the PNC shall first check if there is available capacity in the current superframe, based on the remaining length of the CAP and the desired length of the requested GTS. On receipt of the acknowledgment, the device shall continue to track beacons for a certain time. If the GTS was allocated successfully, the PNC shall set the start slot and the length of the GTS in the GTS descriptor. The PNC shall then include this GTS descriptor in its beacon. The PNC shall also update the *Final CAP Slot* subfield of the beacon frame, indicating the final superframe slot utilized by the decreased CAP. On receipt of a beacon frame containing a GTS descriptor corresponding to its own address, the device shall process the descriptor and start using it immediately.

To request the deallocation of an existing GTS, the device shall send the GTS deallocation request command to the PNC. On receipt of a GTS deallocation request, the PNC shall attempt to deallocate the GTS. The PNC shall also update the *Final CAP Slot* utilized by the increased CAP. The PNC shall add a GTS descriptor into its beacon frame corresponding to the deallocated GTS. The PNC shall be allowed to reduce its CAP below *aMinCAPLength* to accommodate the temporary increase in the beacon frame length due to the inclusion of the GTS descriptor. On receipt of a beacon frame containing a GTS descriptor corresponding to the deallocated GTS, the device shall immediately stop using the GTS.

The deallocation of a GTS may result in the superframe becoming fragmented. The PNC shall ensure that any gaps occurring due to the deallocation of a GTS, are removed to maximize the length of the CAP. For each device with an allocated GTS having a starting slot lower than the GTS being deallocated, the PNC shall update the GTS with the new starting slot and add a GTS descriptor to its beacon corresponding to this adjusted GTS. The new starting slot is computed so that no space is left between this GTS and either the end of the CFP, if the GTS appears at the end of the CFP, or the start of the next GTS in the CFP. In situation where multiple reallocations occur at the same time, the PNC may choose to perform the reallocation in stages. On receipt of a beacon frame, the device shall adjust the starting slot of the GTS corresponding to the GTS descriptor.

As shown in the above, to allocate a GTS, there are two commands need to be exchanged. To deallocate a GTS, two commands need to be exchanged. In terms of the number of message exchanged, the overhead is the same as our proposed scheme. But to maintain the CAP, the PAN coordinator should update the *Final CAP slot*, and all devices should process this subfield every beacon interval, as a result, the power is consumed by this kind of processing overhead. Beacon can be larger by adding descriptors, which results in consuming more energy to process them.

To meet the reallocation policy, all descriptors should be checked with its own GTS by the devices. The devices may consume more energy to compute new slot position by the reallocation. In situation where multiple reallocations occur at the same time, performing the reallocation in stages takes for a long time. Moreover, the overlapping can happen probably on boundary between CAP and CFP, or between GTSs because there is not any acknowledgment from devices before using the reallocated GTS.

3. EE-MAC Design

The main goal in our protocol design is to reduce energy consumption, while supporting Guaranteed Service (GS) efficiently. Because GTS allocation/deallocation/reallocation scheme of IEEE802.15.4 is very complex, our protocol uses a method of allocating an exclusive unique backoff time value to each rt-node requesting GS. As a result, we can provide GS by preventing contention between rt-nodes and also multiplex traffics statistically in time division fashion. Further explanation about the method of allocating an exclusive unique backoff time value will be given in Section 3.4.

The conventional methods like [6][7] for saving energy use the low duty cycle consisting of short active period and long inactive period in beacon mode. But the parameters (i.e., active period, inactive period and beacon interval) on duty cycle are fixed at the initial time of network configuration and deployment, and cannot be changed adaptively. Our protocol proposes an algorithm to change the duty cycle adaptively according to channel utilization of media depending on traffic load.

3.1 Features Adopted from IEEE802.15.4 and IEEE802.11

We adopt the following features from IEEE802.15.4 standard.

1) Topology (e.g., star, peer-to-peer, or cluster-tree),

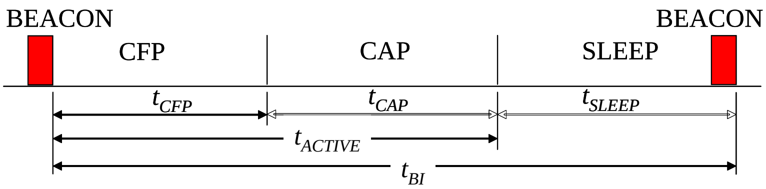
2) Components (e.g., full-function devices, reduced-function device, coordinator, and device),

3) Starting and Maintaining PANs (e.g. ED/active/passive channel scan, association/disassociation, and synchronization procedure).

The adopted features conforms the specifications of IEEE802.15.4. Therefore we will skip the description about them. We also adopt the distributed coordination function (DCF), the backoff scheme and virtual carrier sensing scheme using network allocation vector (NAV) from IEEE802.11 standard [10]. These adopted features will be explained in section 3.3-A and 3.3-B.

3.2 Superframe Structure

We adopt beacon mode to use a superframe structure like IEEE802.15.4. The superframe is bounded by beacon frames sent from the coordinator. A beacon frame is sent in the first slot of each superframe. The beacon frames are needed to synchronize all nodes attached on a PAN, to identify the PAN. The beacon frame just includes the address of a sender, and the time (t_{CFP}) joining with the next CAP and the time (t_{ACTIVE}) joining with the next sleep. Superframe structure shown in **Fig. 1** can have an active and an inactive portion. During the inactive portion, the coordinator does not interact with its neighbor on the PAN and turns off its radio and enter into a low-power sleep mode. The active portion consists of CFP and CAP.



BEACON includes the address of sender, t_{CFP} and t_{ACTIVE}
t_{BI}: Beacon Interval length

Fig. 1. Superframe structure.

If a coordinator tries to transmit the beacon frame, carrier sensing is started at the start of time slot. If any carrier signal is not sensed at the last part of the time slot, the media is immediately occupied and the transmission of the beacon frame is started. This means that the backoff time value for the beacon frame equals zero. In other words, the beacon frame transmission starts immediately if a carrier signal is not sensed within the time slot boundary.

During CFP, GS can be provided to rt-nodes. When an rt-node wants to join to the PAN, it requests association with the coordinator. The coordinator received the request will decide admission by using bandwidth allocation algorithm and allocate a unique backoff time value to the rt-node depending upon the decision result. This backoff time value for the rt-node is unique and dedicated to it on the PAN until it is released by the rt-node. The admitted rt-nodes should run their backoff algorithm with this time value before accessing the medium. The backoff timers will expire at different time, because the admitted rt-nodes have their own unique backoff time that is exclusively assigned. If a backoff timer of an rt-node expires earlier than others, then the rt-node may start transmitting its rt-frames without sensing carrier on that medium. As a result, the assigned backoff time value corresponds to its access priority within CFP. That is, since the node with smaller backoff time value will become the winner against the node with larger backoff time value in the aspect of contention, it looks like contention free. In Section 3.4, we will discuss in more detail.

During CAP, Every non-real-time node (nrt-node) that wants to send nrt-frames has to contend with other nrt-nodes using CSMA/CA algorithm. Every nrt-node should follow the binary exponential backoff procedure like IEEE802.11 and S-MAC before start transmission. Here, nrt-frames include allocation request, release request, and response frame for rt-nodes as well as non-real-time data traffic.

In the IEEE802.15.4 standard, CAP follows the beacon, and in turn, CAP is followed by CFP. Because the CFP is located on the trail part of the superframe, the Final CAP position should be maintained by all devices every beacon interval. On the other hand, our protocol placed CFP after beacon. Rt-nodes have one opportunity to transmit its rt-data per beacon interval. They access the medium without collision by using exclusively allocated backoff time. While rt-nodes are being associated or disassociated, the boundary between CFP and CAP is dynamically moving. The devices (rt-nodes and nrt-nodes) don't care where the boundary is. Because the rt-nodes have higher priority to access the medium than nrt-nodes, naturally rt-traffic is sent on the front part of the superframe. If CFP length is reduced, CAP length is extended. As a result, the statistical time division multiple access scheme is implemented on the medium.

3.3 Nrt-frame Transfer on CAP

3.3.1 CSMA/CA

Because multiple devices may want to transmit frames simultaneously, they need the carrier sense multiple access and collision avoidance mechanism for the medium. Our protocol will completely follow the procedures like IEEE802.11 and S-MAC for collision avoidance, including both virtual and physical carrier sensing. The binary exponential backoff scheme is also adopted.

The basic access method is based on the conventional DCF [10]. The RTS/CTS mechanism is adopted to address the hidden terminal problem [11]. The detailed descriptions about these features can be found in [3][10]. Nevertheless, in the following, we give some descriptions for comprehension.

A station with a new packet to transmit monitors the channel activity. If the channel is idle for a period of time equal to a distributed interframe space (DIFS), the station transmits. Otherwise, if the channel is sensed busy (either immediately or during DIFS), the station persists to monitor the channel until it is measured idle for a DIFS. At this point, the station generates a random backoff interval before transmitting (this is the Collision Avoidance feature of the protocol), to minimize the probability of collision with packets being transmitted by other stations.

The data backoff time is derived by DBT=RAND (0, CW) x *BackoffSlot_time*, where RAND (0, CW) returns a pseudo-random integer within interval [0, CW], which CW grows exponentially for each retransmission attempt and the range of CW is from CW_{min} to CW_{max}. In the IEEE802.11 standard, CWmin and CWmax are set as 32 and 1024, respectively. That is $CW = CW_{min} \times 2^r < CW_{max}$ where r is the number of retransmission times. The *BackoffSlot_time* (t_{BS}), which is defined as the time needed at any station to detect the transmission of a packet from any other station. It depends on the physical layer, and it accounts for the propagation delay, for the time needed to switch from the receiving to the transmitting state, and for the time to signal to the MAC layer the state of the channel (busy detect time).

The backoff timer is decremented as long as the channel is sensed idle. It is "frozen" when a transmission is detected on the channel, and reactivated when the channel is sensed idle again for more than a DIFS.

When the backoff time reaches zero, instead of transmitting the DATA packet immediately, the station preliminarily transmits a special short frame called RTS. When the receiving station detects an RTS frame, it responds, after a short inter frame space (SIFS), with a CTS. The transmitting station is allowed to transmit its DATA packet after a SIFS only if the CTS frame is correctly received. Because SIFS is smaller than t_{BS}, there is no carrier sensing happened during SIFS.

The duration field is included in each transmitted frame, which indicates how long the remaining transmission will be. Therefore, neighbor nodes which receive a frame destined to another node, know how long they should keep silent. The nodes record this value into their NAV timer [10]. The medium is busy until the NAV timer fires. When a node has data to send, it first looks at the NAV timer. If its value is not zero, the node determines that the medium is busy. This is called virtual carrier sense. Physical carrier sense is performed at the physical layer by listening to the channel for possible transmissions. The medium is determined as free if both virtual and physical carrier sense indicates free.

All senders should obtain the medium by performing carrier sensing accompanied with backoff procedure. If a node fails to get the medium, it goes to sleep and wakes up when the receiver is free and listening again.

The broadcast frame is transmitted without using RTS / CTS. But the unicast frame follows the sequence of RTS / CTS / DATA / ACK between the sender and the receiver.

3.3.2 Overhearing Avoidance

Overhearing happens because a node picks up packets that are destined to other nodes. We also adopted the approach used in IEEE802.11 to avoid overhearing like S-MAC. This approach tries to avoid overhearing by letting interfering nodes go to sleep after they hear an RTS or CTS packet. Since DATA packets are normally much longer than control packets, the approach prevents neighboring nodes from overhearing long DATA packets and the following ACKs. All immediate neighbors of the sender and the receiver should sleep after they hear the RTS or CTS packet until the current transmission is over. Each node maintains the NAV to indicate the activity in its neighborhood. When a node receives a packet destined to other nodes, it updates its NAV by the duration field in the packet. A non-zero NAV value indicates that there is an active transmission in its neighborhood. Thus a node should sleep to avoid overhearing if its NAV is not zero. It can wake up when its NAV becomes zero.

3.4 Rt-frame Transfer on CFP

Rt-nodes which want to send an rt-frame need to be allocated their bandwidth required for sending the rt-frame. At first the rt-node has to request the allocation of bandwidth to its coordinator, and then if its request is accepted, it will be assigned a backoff time value by its coordinator. The coordinator can accept or reject the request from each node according to the bandwidth allocation algorithm using Bandwidth Allocation Table (BAT).

3.4.1 A. Bandwidth Allocation & Admission Control Algorithm

Table 1. BAT structure.

Backoff time value	Device Address	Allocation	Requested bandwidth
1	#AAAA	Allocated	
2	#BBBB	Allocated	
3	#CCCC	Allocated	
4	-	Free	
⋮	⋮	⋮	
n	-	Free	

Table 1 shows the BAT structure. There are n entries. Each entry has an exclusive (and unique) backoff time value. The backoff time value set is {1, 2, 3,..., n}. Here, n is determined depending upon the number of rt-nodes which can be served in the PAN on a CFP. We assume n as 7 since 7 GTSs allocation is possible in IEEE802.15.4 standard.

If a device sends the allocation request command to its coordinator, the coordinator should determine whether to accept or reject depending on the available bandwidth for this request. This admission control can be achieved by operating and managing BAT.

The coordinator processes each request on first come first service basis. The frame length in the amount of demanded bandwidth is included in the allocation request command. When the coordinator is requested for bandwidth allocation from an rt-node, it checks the condition given by equation (2) in section 3.4-C. If the condition is satisfied, it chooses a free entry having the smallest backoff time value in BAT. In the chosen entry, the device address field is written with the rt-nodes's address, and marked as 'allocated'. The backoff time value of this chosen entry is replied to the rt-node. If the equation (2) is not satisfied or if there is no free entry in BAT, this request is rejected. In **Table 1**, we can see BAT status that three entries are allocated to three different rt-nodes and the others are left free.

3.4.2 B. Contention Free Operation

After receiving response command with the unique backoff time value, the rt-node is ready to send an rt-frame on CFP. After beacon, the rt-nodes stay in backoff state during their given backoff time. Because their backoff time values are unique (and exclusive) in the CFP, their backoff timers will expire at different time. The rt-node whose backoff timer expires early, sends a RTS for transmitting its rt-frame without carrier sensing. Although carrier sensing is not taken place, any collision will not occur because of using exclusively chosen backoff time. As a result, the allocated backoff time value corresponds to its access priority order within a CFP. That is, since the node with smaller backoff time value will become a winner against the node with larger backoff time value in the aspect of contention, media access operation looks like contention free.

Rt-frame transmissions through the backoff procedure are illustrated in **Fig. 2**. Here, we assume the status of BAT like **Table 1**. **Fig. 2** shows that rt-frames from three different rt-nodes are transmitted in sequence without collision. To illustrate rt-frame transfer mechanism simply, 'Send rt-packet' in **Fig. 2** and **Fig. 3** means RTS/CTS/DATA/ACK sequence whose elements are spaced with a SIFS. Like transferring nrt-frame, handshaking of RTS/CTS is used to prevent the hidden terminal problem.

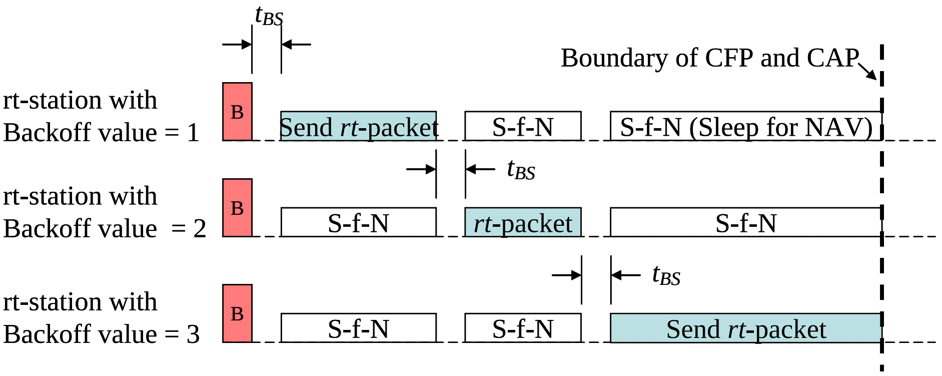


Fig. 2. Three rt- nodes are allocated.

Let's assume rt- node (#AAAA)'s backoff time value is 1, rt-node (#BBBB)'s backoff time value is 2, and rt- node (#CCCC)'s backoff time value is 3. In **Fig. 2**, rt-node (#AAAA) can start a transmission after 1 t_{BS} after the beacon since its backoff timer expires first. But the other nodes remain in backoff state since their backoff timer still running. When the rt-node (#AAAA) starts transmission, the NAV timers in the other nodes are set with the duration field value in the transmitted frame header and starts running. At this time, the other nodes' backoff timers stop running until the NAV timers expire. If the NAV timer expires, the backoff timer of the node in backoff state runs again.

After 1 t_{BS}, rt-node (#BBBB) starts its transmission since its backoff timer expires next. The NAV timers of nodes except rt-node(#BBBB) are also set with the duration field value of rt-node (#BBBB)'s frame header. Rt-node (#CCCC) still remains in backoff state until the NAV timer expires. After 1 t_{BS}, rt-node (#CCCC) obtains transmission opportunity.

Node acts differently depending upon the transmitted frame is destined to itself or not. If a packet is destined to itself, it will receive the frame. Otherwise, it avoids overhearing by turning off its radio, after it sets the NAV timer with the duration field of the frame header.

When rt-node (#BBBB), whose the backoff time value is 2, wants to quit using the allocated bandwidth, it sends the release request command to its coordinator. The coordinator releases and marks the entry as free. The changed BAT is as shown in **Table 2**. The transmission activity on a media is shown in **Fig. 3**.

Table 2. BAT structure after one entry is released.

Backoff time value	Device Address	Allocation	Requested bandwidth
1	#AAAA	Allocated	
2	-	Free	
3	#CCCC	Allocated	
4	-	Free	
⋮	⋮	⋮	
n	-	Free	

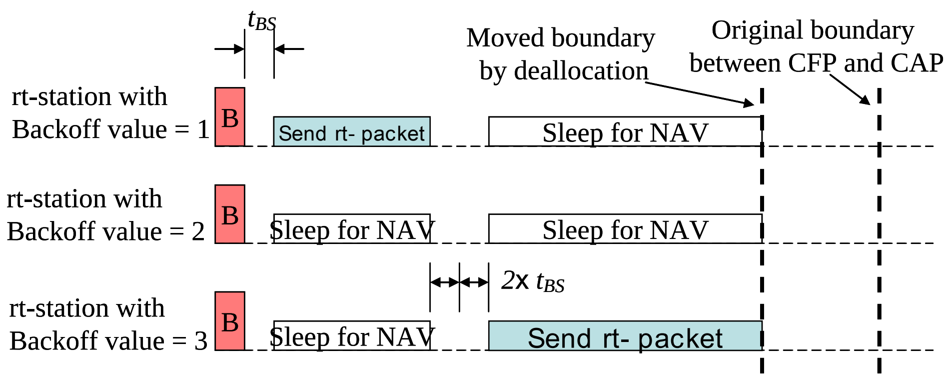


Fig. 3. Transmission activity after one node terminates.

Fig. 3 shows the case where the rt-node (#BBBB) is removed by terminating its transmission. The rt-node (#AAAA) still has the first transmission opportunity after beacon. Following the transmission of the rt-node (#AAAA), the rt-node (#CCCC) can obtain the transmission opportunity immediately after 2 t_{BS} . When the node having smaller backoff time value terminates first, at least, 1 t_{BS} time loss will be happen.

Although backoff time reallocation scheme may be considered to prevent such loss, we do not use reallocation method. The nodes continue to operate with the assigned backoff time value earlier. This scheme can slightly cause inefficiency in channel utilization. For example, in the case that just only one node with the largest backoff time value = 7 remains on the medium, it takes 7 t_{BS} time before transmission. But this overhead is trivial. From this result, we have decided that a DIFS value should be larger than 7 t_{BS}.

Therefore, rt-node always has higher priority than nrt-node. Beacon frame does not need to include the information (e.g., *Final CAP slot* in IEEE802.15.4) about the boundary between CAP and CFP. Each device does not care where the boundary is. The boundary between CAP and CFP is automatically moving according to the rt-traffic load as shown in **Fig. 3**. So, CAP can be maximized efficiently.

Another operation mode can be considered is to use the explicit boundary (t_{CFP}) given by equation (1), which tells when the beginning time of CAP is. If we use this mode, a DIFS value can be smaller than 7 t_{BS}.

If we want to reallocate backoff time value, we may add descriptors with the reallocated backoff time into the beacon frame. These descriptors should be interpreted by the corresponding nodes. These reallocation procedures may be very complicate and it requires more processing power as the case of IEEE802.15.4 when we discussed in Section 2. Therefore, our scheme does not use the reallocation scheme.

Because the reallocation is not used, our scheme is very simple. Moreover, our scheme can guarantee the real-time service for rt-nodes no matter what the backoff time is. It means that one transmission opportunity is guaranteed to all rt-nodes every superframe cycle.

In CFP, rt-node is not permitted to retransmit a failure rt-packet like other real-time protocols, e.g., IEEE802.15.4. It is because the guaranteed bandwidth was already wasted by the failure in this superframe, and besides, the retransmission may cause collisions and increasing variance of delay.

3.4.3 The Length of CFP (t_{CFP})

t_{CFP} means the duration of CFP. Its value can be calculated according to the following equation.

$$t_{CFP} = \frac{\sum_{i=1}^{n} BW_i}{S} + \max.BackoffTime\_Value \times t_{BS}, \tag{1}$$

where BW_i means the bandwidth requested by node or allocated to node. The product term of max. Backoff time_Value and t_{BS} means the time needed for backoff processing. When the sum of BW_i is divided by the media transmission speed (S), the result means the time needed for transmitting the pure rt-frames.

The PAN coordinator shall preserve the minimum CAP length following the rule.

$$t_{CFP} < t_{BI} - t_{SLEEP} - aMinCAPLength \tag{2}$$

This ensures that MAC commands can still be transferred to devices when GSs are being used.

3.5 Adaptive Adjusting Duty Cycle Control Scheme

Energy consumption of a node can be reduced by sleeping during inactive period. Conventional methods like IEEE802.15.4 and S-MAC use the fixed length in time for an active and inactive period. After a PAN is deployed, they cannot change these parameters during operation.

To reduce energy consumption, the longer inactive period, i.e., the shorter active period, is advantageous when the traffic load is low. Whereas, when the traffic load is high, the active period of BI should be increased.

Therefore, we propose an algorithm to adjust the duty cycle with the fixed length of BI.

The length of BI for synchronization should not be changed during operation. Instead, we adjust the duty cycle by changing the portion of the active period or the inactive period over the fixed length of BI. The duty cycle is defined as the portion of the active period over the length of BI, i.e., Duty Cycle (%) = t_{ACTIVE} / t_{BI} = 1- t_{SLEEP}/ $t_{BI.}$. Thus, the duty cycle can be adaptively adjusted by controlling t_{SLEEP} according to the channel utilization.

3.5.1 tSLEEP Adjusting Algorithm

After getting the channel utilization (U_{CH}) of the previous superframe cycle, U_{CH} is compared with a certain threshold level. t_{SLEEP} is adjusted dynamically because U_{CH} varies according to the traffic characteristic and change.

if ($U_{CH} < U_{lower\_threshold}$) $t_{SLEEP} = t_{SLEEP}/\ \alpha$;
else if ($U_{CH} > U_{upper\_threshold}$) $t_{SLEEP} = t_{SLEEP} * \alpha$;
else $t_{SLEEP} = t_{SLEEP}$;

Here, α is the weight factor, where $0 < \alpha < 1$.

3.5.2 Channel Utilization

The coordinator calculates the channel utilization considering the following policies while monitoring the media.

Policy 1: U_{CH} is regarded as media occupancy ratio for frame transmission. $U_{CH}=\sum t_{tx}$ / $t_{BI.}$ Here, t_{tx} means the transfer time for each packet.

Policy 2: The sum of Tx_Q (Pending message queue for each node) and Rx_Q (Receiving from nodes) size of the coordinator is normalized. It is regarded as channel utilization.

Since IEEE 802.15.4 uses indirect transmission, network traffic load can be calculated in terms of Tx queue size and Rx queue size of the coordinator.

$$U_{CH} = NORMALIZE(\sum_i Tx\_Queue\_Size\_for\_Node(i) + Rx\_Queue\_Size)$$

Policy 3: Mobile devices can move in or out of the coverage of the coordinator. U_{CH} is calculated by dividing the number of associated device by the number of maximum allowed devices.

U_{CH} = The number of associated devices / The number of maximum allowed devices.

If the traffic pattern is homogeneous, the variance of the channel utilization will be very small and the mean value of U_{CH} will be maintained within a certain threshold level. In this case, t_{SLEEP} will not be changed frequently. But in the case that several events happen in burst and asynchronously, the aggregated traffic pattern looks like burst and shows correlated characteristic. In this situation, the adaptive adjusting algorithm can be quite effective.

4. Energy Consumption and Delay Analysis

Our analysis only considers a PAN, where all nodes can directly hear from each other. η_{tx}, η_{rx}, η_{sleep}, and η_{cs} are the energy dissipated per unit time when in transmit mode, receive mode, sleep mode, and carrier sense mode, respectively. N is the total number of sensor nodes associated with the coordinator in the network. λ_s and λ_c are the total generating rates for packets originating from the sensor node side and the coordinator side, respectively. We assume that all sensor nodes generate one packet per beacon interval, and the generated packets are all destined for the coordinator. We assume that packets generated by the coordinator are destined to the associated nodes (*N*) and one packet per node is sent every beacon interval. t_{BS} is the backoff slot time needed for a station to detect a packet. It accumulates the time needed for the propagation delay, the time needed for switch from the receiving state to the transmitting state, and the time to signal to the MAC layer the state of the channel (busy detect time). Because our protocol uses the binary exponential backoff scheme, the backoff time of each node is a random variable which is determined by RAND(0, CW) x t_{BS} where RAND( ) returns a pseudo-random integer within interval [0, CW]. $\overline{T}_{BoFF-ECF}$ is the average backoff time to get a chance to transmit, which is calculated as $\overline{T}_{BoFF-ECF} = CWt_{BS}/2$. To simplify the analysis, we assume that there is only one contention phase in EE-MAC, so the contention window size (CW) is fixed at the initial value 32 as in IEEE802.11. $\overline{T}_{RTS}$, $\overline{T}_{CTS}$, $\overline{T}_{DATA}$, $\overline{T}_{ACK}$ and $\overline{T}_{BEACON}$ are the average time required to transmit a RTS packet, CTS packet, DATA packet, ACK packet, and BEACON, respectively.

In the following expressions $\overline{P}_{tx-s}$, $\overline{P}_{rx-s}$, $\overline{P}_{rx-s-NAV}$, and $\overline{P}_{SLEEP-s}$ represent the average power dissipated when a sensor node is in transmit mode, receive mode not using NAV, receive mode using NAV, and sleep mode, respectively.

$$\overline{P}tx-s = \eta tx\lambda s(\overline{T}RTS + \overline{T}DATA) + \eta tx(\lambda c/N)(\overline{T}CTS + \overline{T}ACK) + \eta cs\lambda s\overline{T}BoFF-ECF \tag{3}$$

$$\overline{\mathrm{P}}_{rx-s} = \eta_{rx}(t_{BI} - t_{SLEEP})/t_{BI} \tag{4}$$

$$\overline{\mathrm{P}}_{rx-s-NAV} = \eta_{rx}(t_{BI} - t_{SLEEP})/t_{BI} - \eta_{rx}\lambda_{oh} + \eta_{SLEEP}\lambda_{oh} \tag{5}$$

$$\lambda_{oh} = (\lambda_c((N-1)/N) + \lambda_s N)(\overline{T}CTS + \overline{T}DATA + \overline{T}ACK) \tag{6}$$

Here, λ_{oh} means the arrival rate caused by overhearing. In equation (5), the second term means the power dissipation caused by overhearing because this effect already has included in the first term. And then the third term has to be added because our scheme makes node sleep during overhearing.

$$\overline{P}_{SLEEP-s} = \eta_{sleep} t_{SLEEP}/t_{BI} \tag{7}$$

In the following expressions $\overline{P}_{tx-c}$, $\overline{P}_{rx-c}$, $\overline{P}_{rx-c-NAV}$, and $\overline{P}_{SLEEP-c}$ represent the average power dissipated when a coordinator node is in transmit mode, receive mode not using NAV, receive mode using NAV, and sleep mode, respectively.

$$\begin{aligned}\overline{P}_{tx-c} = \eta_{tx}(\lambda_c\overline{T}_{RTS} + \lambda_c\overline{T}_{DATA} + \mathrm{N}\lambda_s\overline{T}_{CTS} + \mathrm{N}\lambda_s\overline{T}_{ACK})\\ + \eta_{cs}\lambda_c\overline{T}_{BoFF-ECF} + \eta_{tx}\overline{T}_{BEACON}/t_{BI}\end{aligned} \tag{8}$$

$$\overline{\mathrm{P}}_{rx-c} = \overline{\mathrm{P}}_{rx-c-NAV} = \eta_{rx}(t_{BI} - t_{SLEEP})/t_{BI} \tag{9}$$

$$\overline{P}_{SLEEP-c} = \eta_{sleep} t_{SLEEP}/t_{BI} \tag{10}$$

For both the sensor node and coordinator node, the average power consumption can be computed as following.

$$\overline{P}_{ECF-device} = \overline{P}_{tx-s} + \overline{\mathrm{P}}_{rx-s} + \overline{P}_{SLEEP-s} \tag{11}$$

$$\overline{P}_{ECF-device-NAV} = \overline{P}_{tx-s} + \overline{P}_{rx-s-NAV} + \overline{P}_{SLEEP-s} \tag{12}$$

$$\overline{P}_{ECF-coordinator} = \overline{P}_{tx-c} + \overline{P}_{rx-c} + \overline{P}_{SLEEP-c} \tag{13}$$

$$\overline{P}_{ECF-coordinator-NAV} = \overline{P}_{tx-c} + \overline{P}_{rx-c-NAV} + \overline{P}_{SLEEP-c} \tag{14}$$

To compare the performance with IEEE802.15.4, we derived the equations for the average power consumption of IEEE802.15.4 devices and coordinator.

IEEE802.15.4 shall delay for a random number of complete backoff periods which is determined by RAND(0, 2^{BE} -1) x *aUnitBackoffPeriod*. To simplify the analysis, we assume that carrier sensing successes in the first contention window.

$\overline{T}_{BoFF-15.4}$ is the average backoff time to get a chance to transmit. The average backoff time is calculated as $\overline{T}_{BoFF-15.4} = \{(2^{BE}-1)/2+1\} \times aUnitBackoffPeriod$.

$$\overline{P}_{tx-s-15.4} = \eta_{tx}\lambda_s\overline{T}_{DATA} + \eta_{tx}(\lambda_c/\mathrm{N})\overline{T}_{ACK} + \eta_{cs}\lambda_s\overline{T}_{BoFF-15.4} \tag{15}$$

$$\overline{P}_{rx-s-15.4} = \overline{P}_{rx-c-15.4} = \eta_{rx}(t_{BI}-t_{SLEEP})/t_{BI} \tag{16}$$

$$\overline{P}_{SLEEP-s-15.4} = \overline{P}_{SLEEP-c-15.4} = \eta_{sleep}\, t_{SLEEP}/t_{BI} \tag{17}$$

$$\overline{P}_{tx-c-15.4} = \eta_{tx}(\lambda_c\overline{T}_{DATA} + \mathrm{N}\lambda_s\overline{T}_{ACK}) + \eta_{cs}\lambda_c\overline{T}_{BoFF-15.4} + \eta_{tx}\overline{T}_{BEACON}/t_{BI} \tag{18}$$

$$\overline{P}_{15.4-device} = \overline{P}_{tx-s-15.4} + \overline{P}_{rx-s-15.4} + \overline{P}_{SLEEP-s-15.4} \tag{19}$$

$$\overline{P}_{15.4-coordinator} = \overline{P}_{tx-c-15.4} + \overline{P}_{rx-c-15.4} + \overline{P}_{SLEEP-c-15.4} \tag{20}$$

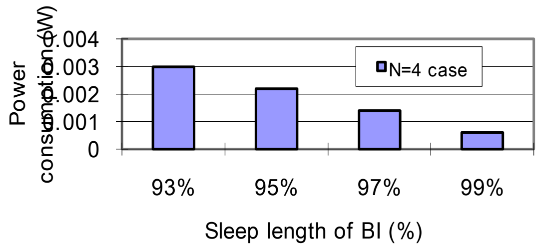


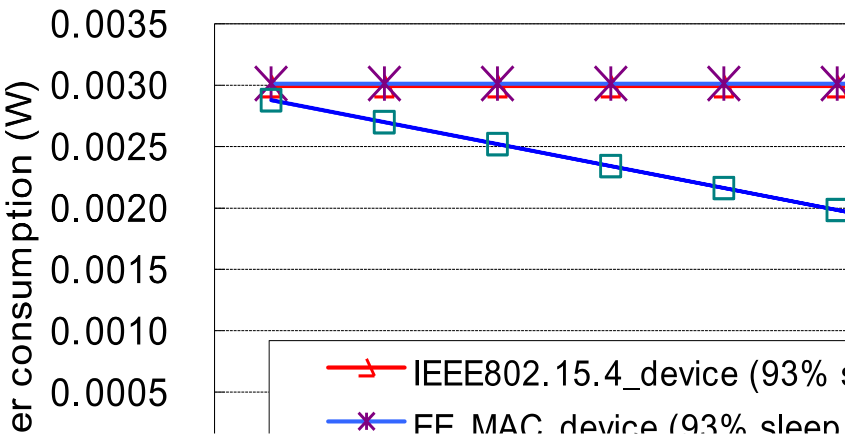
Fig. 4. Power consumption vs. t_{SLEEP} length.

Nominal Values for parameters used in energy analysis are assumed as follows. η_{tx} = 60mW, η_{rx} = 40mW, η_{sleep} = 90μW, η_{cs} =40mW, λ_s =1/ t_{BI}, λ_c =$N\lambda_s$, t_{BS} = 20μs for DSSS PHY, and $\overline{T}_{RTS}$ = $\overline{T}_{CTS}$ = $\overline{T}_{ACK}$ = 0.32ms, $\overline{T}_{DATA}$ = 1.6ms, $\overline{T}_{BEACON}$ = 0.64 ms, CW=32, *BE*=3, *aUnitBackoffPeriod* (20symbols)= 312μs, and t_{BI} = 2s.

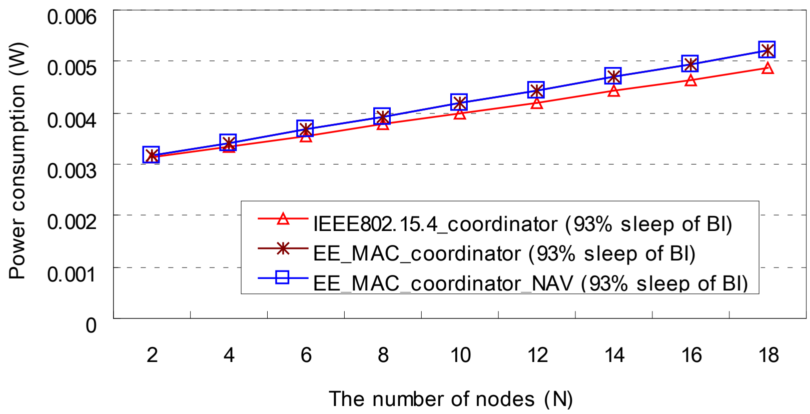
Analysis should be performed within the stable state. System load and the stable condition are given by $\rho = (N\lambda_s + \lambda_c) \times (\overline{T}_{RTS} + \overline{T}_{CTS} + \overline{T}_{DATA} + \overline{T}_{ACK}) < (1 - t_{SLEEP}/t_{BI})$.

At first, we evaluate how the sleep interval length effects the power consumption in the case of N=4. As shown in **Fig. 4**, the longer the sleep length is, the less power consumption is. This result is absolutely true for the both of IEEE802.15.4 and EE_MAC. Our proposed scheme was compared with the conventional IEEE802.15.4. Fig. 5 (a) shows the power consumption of device node according to the number of the associated nodes in the case of 93% sleep of beacon interval. EE_MAC without using NAV scheme dissipates the power slightly higher than IEEE802.15.4. The reason is that the power is dissipated for exchanging

RTS/CTS because EE_MAC uses RTS/CTS/DATA/ACK scheme. But we can solve the hidden terminal problem. As the number of associated device node is increased, the more packets will be sent because we assumed that all nodes generate one packet every beacon interval. For the duration sending these packets, the other nodes in IEEE802.15.4 and EE_MAC without NAV dissipate η_{rx} energy per unit time to receive or overhear them. On the other hand, the nodes in EE_MAC with NAV dissipate η_{sleep} energy. As a result, in the case of EE_MAC with NAV, the more power is saved by avoiding overhearing according that N is increased.



(a)



(b)

Fig. 5. Comparison of power consumption.

Fig. 5-(b) shows the power consumption of coordinator node according to the number of the associated nodes in the case of 93% sleep of beacon interval. In the case of coordinator, EE_MAC with NAV and EE_MAC without NAV dissipate the same amount power. The reason is that there is no overhearing because we assumed that all devices send every packet to their coordinator. EE_MAC scheme dissipates the power slightly higher than IEEE802.15.4. The reason is that the power is dissipated for exchanging RTS/CTS.

According to **Fig. 4** and **Fig. 5**, the coordinator's power consumption is proportional to N and the duty cycle. The power consumption of device node in the case of IEEE802.15.4

and EE_MAC without NAV is independent with N, but still proportional to the duty cycle. Using EE_MAC with NAV, more power can be saved in the device node.

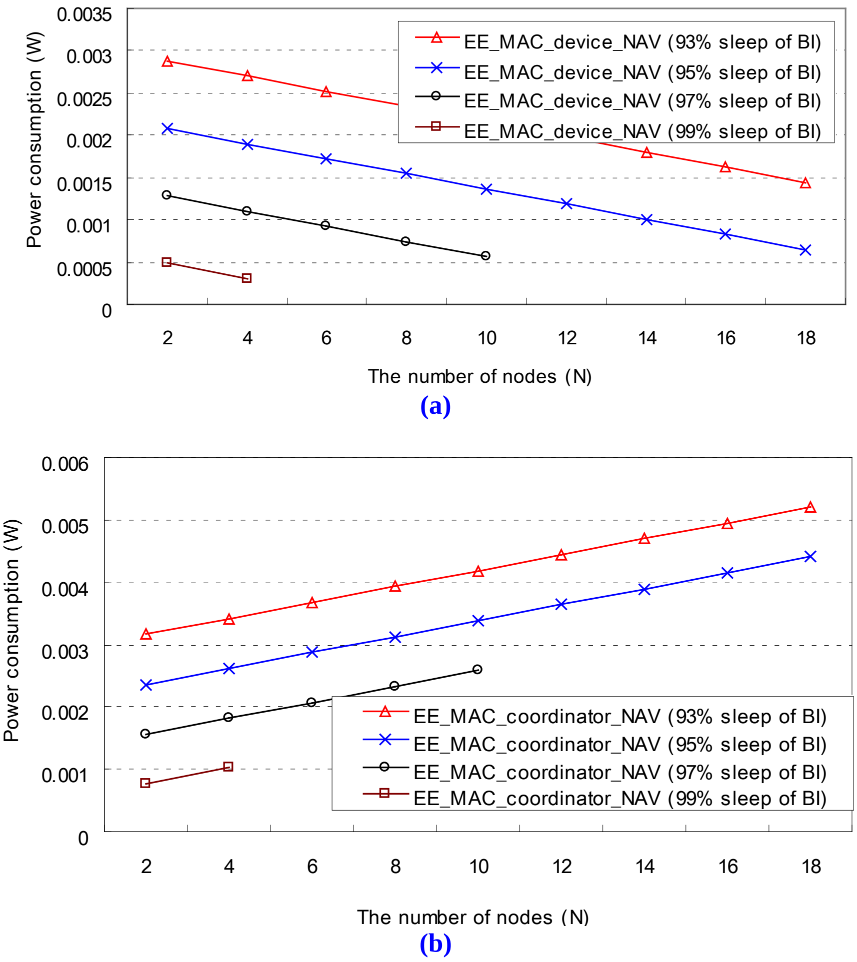
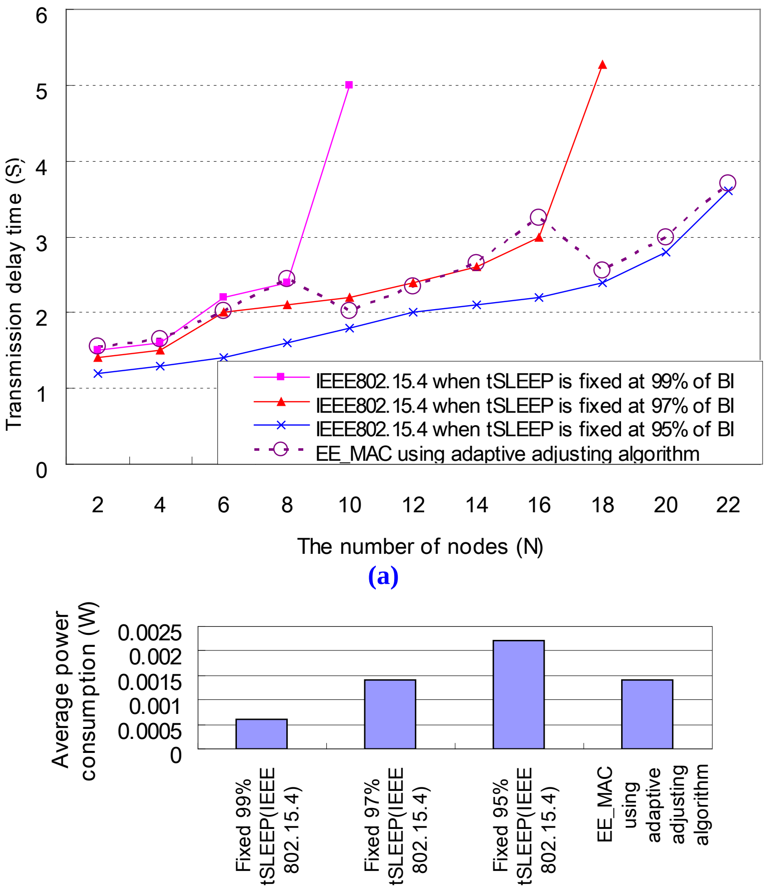


Fig. 6. Power consumption of EE_MAC with NAV.

Fig. 6-(a) compares the power consumption of EE_MAC device node with NAV according to the number of the associated nodes under varying the duty cycle. Power consumption is also proportional to the duty cycle. The more power is saved by avoiding overhearing according that N is increased. This result is in accordance with the results of **Fig. 4** and **Fig. 5**. **Fig. 6-(b)** shows the power consumption of EE_MAC coordinator node without using NAV according to the number of the associated nodes under varying the duty cycle. Power consumption is also proportional to the duty cycle. This result is in accordance with the result of **Fig. 4** and **Fig. 5**.

EE-MAC was implemented in the network simulator Sim++[12]. Our simulation modeled a network of one PAN coordinator and 30 devices placed randomly within a 50 *50 square meter area. Each node has a radio transmission range of 15m, interference range of 30m and channel capacity of 250Kbps. Data packet size is 16bytes. The packet length of RTS is 8bytes. The packet length of CTS is 8bytes. The packet length of ACK is 8bytes. SIFS=10㎲, DIFS=160㎲. Beacon interval t_{BI} = 2s. Traffic from each node is generated as constant bit rate (50bits/s). No node mobility is assumed. Simulation time is 2000s.



(b)

Fig. 7. Transmission delay time and average power consumption (Policy 3: α=0.98, $U_{lower\_threshold}$ = 8/20, $U_{upper\_threshold}$=16/20)).

Fig. 7-(a) compares the transmission delay time of EE_MAC with the adaptive adjusting algorithm with IEEE802.15.4 standard with the fixed duty cycle according to the traffic load (N). In the case that 99% of beacon interval is fixed for sleeping, PAN cannot service over N=10 and will be fallen in the unstable state because the fraction of active period is very small. The transmission delay will be increased rapidly at N=8. In the case that 97% of beacon interval is fixed for sleeping, PAN can service the more number of nodes than 99% case. But 97% case can not still service over N=18 and will be fallen into the unstable state. IEEE802.15.4 standard can not change the duty cycle in the middle of operation.

For simplicity, EE_MAC uses the policy 3 to adjust the sleep length. Algorithm is applied with weight factor α=0.98, $U_{lower\_threshold}$=8/20, and $U_{upper\_threshold}$=16/20. As shown in **Fig. 7-(a)**, even though the number of the associated node cross over a certain threshold value, PAN still remains in the stable state by increasing or decreasing the sleep period.

If we shorten the active time duration (that is, longer sleep period) than the time duration required by the current traffic load, energy wasting will not be occurred, but PAN is unstable. If we increase the active time duration (that is, shorter sleep period) than the time duration required by the current traffic load, PAN is stable, but energy wasting may be occurred.

The adaptively adjusting algorithm can also reduce the average power consumption as shown in **Fig. 7-(b)**. The bar graphs are plotted with the averaged values for different N values.

Fig. 8 shows the delay time of rt-traffic and nrt-traffic on the two cases. One is the case twothat 2 rt-nodes are allocated and the other is the case that 4 rt-nodes allocated. The delay time is evaluated according to the traffic load (N). The delay time of rt-traffic is determinant. On the other hand, the delay time of nrt-traffic in the case of rt-nodes=2 becomes shorter than the case of rt-nodes=4. It is because the bandwidth which is not used by rt-nodes, can be used by nrt-nodes.

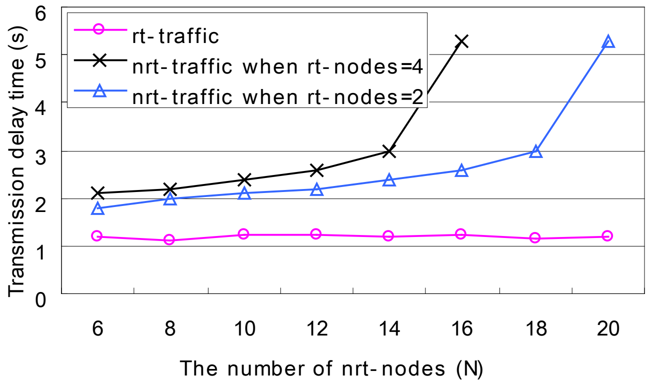


Fig. 8. Transmission delay time (t_{SLEEP}=95%).

5. Conclusions

In this paper, we proposed EE-MAC protocol. The main goal in our protocol design is to reduce energy consumption, while providing guaranteed service efficiently. Instead of IEEE 802.15.4 method which allocates slots absolutely in allocation /deallocation /reallocation process, EE-MAC was proposed the exclusively allocated backoff scheme which assigns a unique backoff time value to each rt-node based on bandwidth allocation and admission control. This scheme can avoid collision between rt-nodes by controlling distributed fashion and take effect a statistical time division multiple access.

The adaptive adjusting duty cycle algorithm is also proposed to save power consumption depending on the traffic load. This algorithm can prolong network lifetime by reducing the amount of energy wasted on idle listening.

Finally, we evaluated the performance in two aspects of power consumption and delay time. The results showed that our protocol can provide guaranteed service efficiently while saving power consumption under varying traffic load condition.

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