M. S. Thesis

Downlink data transmission structure for high-density and large-scale sensor networks

대규모 고밀도 무선 센서 네트워크에서 하향 링크 전송 기법에 관한 연구

by

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Abstract

In this thesis, we consider downlink data transmission in high density and large scale wireless sensor networks where the network coordinator is connected to a large number of child devices in a multi-hop passion. We first propose the use of a dynamic frame structure (DFS) comprising a management frame and a main frame at every beacon interval. During the management frame, parent and child devices can transmit and receive a control message to maintain the network connectivity and to utilize the main frame. During the main frame, only a pair of devices comprising a parent device and its child device can transmit/receive data packets while the other devices stay in an inactive mode to minimize power consumption. The proposed DFS can provide reliable transmission of control messages even in the presence of co-channel interference (CCI) by repeatedly transmitting beacon frames and data request messages. It can provide high transmission capacity in CCI environments by selecting an appropriate packet length and deferring packet transmission. We also design a resource allocation protocol that allows multiple networks nearby to work without collision. Finally, we consider an application of DFS to the IEEE 802.15.4e distributed synchronous multi-channel extension (DSME) protocol.

Keywords: Downlink, wireless sensor network, co-channel interference

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1. Introduction

Recent technology advances make it possible to construct large-scale wireless sensor network systems (WSNs) such as wireless price tag systems, where the tag displays product information of up to a few tens Kbytes [1-2]. The price tag system can manage a very large number of price tags densely located in a small shop area while forming a multi-hop wireless network. It is managed by a gateway (GW) device connected to a main server. Since the wireless price tags are battery-powered, the use of a low-power transceiver such as IEEE 802.15.4 PHY is indispensible [3]. However, medium access control (MAC) protocol for IEEE 802.15.4 may not be suitable for high-volume data transmission in a multi-hop network in the presence of co-channel interference (CCI).

Polling is a classical asynchronous transmission method. It does not require synchronization among devices and thus allows devices to manage their sleep pattern individually, which may significantly reduce implementation complexity and power consumption as well. However, since the parent device does not know the wake-up schedule of its child devices, it must always activate their receivers, resulting in so-called "idle listening" problem which indicates the waste of power even in the absence of signal to receive. Polling message and corresponding acknowledgement (ACK) require large protocol overhead, which may significantly degrade the throughput performance in the presence of CCI (e.g., WLAN). Finally, polling message may be vulnerable in the presence of contention and hidden-node collision, which may seriously degrade the throughput performance in a densely formed wireless sensor network.

The use of a synchronous MAC protocol (e.g., IEEE 802.15.4 fixed frame structure (FFS)) may alleviate the idle listening problem. The FFS can save the power consumption with the use of duty-cycling. However, it cannot completely resolve the idle listening problem, since the duration of the active period remains unchanged even in the absence of signal to transmit or receive. The idle listening problem can be alleviated by making the duration of the active period (i.e., duty-cycle) very short, which may in turn lead to longer data transmission time. Thus, there exists a trade-off between the power consumption in the absence of data to transmit/receive and the data transmission speed in the presence of data to transmit/receive.

Downlink transmission in the IEEE 802.15.4 FFS employs a pending method. Since it requires for a data request and corresponding ACK for the transmission of each packet, it may still suffer from protocol overhead. If the length of the data request message is the same as that of polling message, the protocol overhead of the pending method is the same as that of the polling method. The pending method is more susceptible than the polling method in the presence of CCI since the loss of the beacon frame results in no data transmission during the whole active period, while the packet error rate (PER) increases due to the protocol overhead for the data packet transmission.

In this thesis, we design a downlink transmission structure in high density and large scale wireless sensor networks, where the network coordinator manages a very large number of devices in a multi-hop passion. We first design a dynamic frame structure (DFS) comprising a management frame and a main frame at every beacon interval. During the management frame, parent and child devices transmit and receive a control message to maintain the network connectivity and to utilize the main frame. During the main frame, only a pair of devices (i.e., a parent device and its child device) can transmit/receive data packets while the other devices stay in an idle mode to alleviate the idle listening problem. The proposed DFS can reliably transmit control messages even in the presence of CCI by repeatedly transmitting beacon frame and data request message. During the main frame, the DFS can provide high transmission capacity in the presence of CCI by appropriately selecting the packet length and performing channel sensing before the signal transmission. We also design a resource allocation protocol that allows multiple networks nearby to operate without collision. Finally, we consider an application of DFS to the IEEE 802.15.4e distributed synchronous multi-channel extension (DSME) protocol.

The rest of this thesis is organized as follows. Chapter 2 describes the system model in consideration. Chapter 3 analyzes conventional downlink MAC protocols applicable to WSNs. Chapter 4 describes the proposed downlink transmission structure. Section 5 evaluates the performance of the proposed scheme by computer simulation. Finally, conclusions are given in Chapter 6.

2. System model

Consider a multi-layered network comprising a server and multiple gateways (GWs) and wireless devices, as illustrated in Fig. 2.1. The server and GWs are connected with high-rate links and each GW form a multi-hop WSN. While the server and GWs are cable-powered, the wireless devices are battery-powered. The number of devices in a WSN may be up to a few thousands.

We assume that the downlink data transmission period is long (e.g., once or twice per day) but the size of data to each wireless device may be up to a few tens Kbytes.

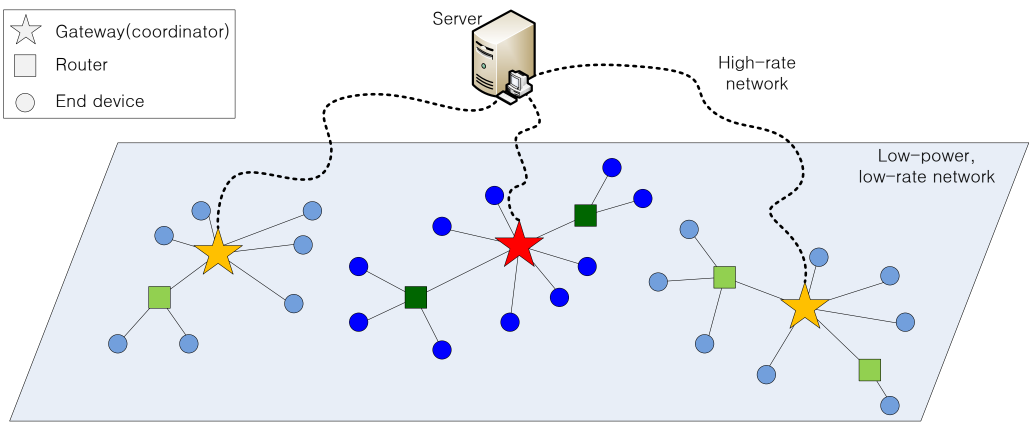


Fig. 2. 1. System model

We also assume that the link between the server and the GWs has capacity large enough to yield no congestion.

In this thesis, we call a GW as the coordinator, implying the management of WSN. To construct a multi-hop WSN, there may be routers which bridges wireless devices. We refer a parent device to a device which has a network depth (i.e., the number of hops to the coordinator) is the less than its child devices by one. For example, the coordinator operates only as a parent, an end device operates only as a child device and a router may operate as both a parent and a child device.

3. Previous works

3.1. Polling

Polling is a classical asynchronous downlink transmission method, where child devices send a polling message to find if their parent device has data to send. If the parent device receives a polling message, it replies by sending an acknowledgement (ACK). If it has data for a child device that send the polling message, it transmits the data to the child device. The child device turns the receiver on until it receive the data, and sends an ACK after successful reception. The polling method does not require synchronization among devices and the end devices can manage its sleep pattern individually, which greatly reduce implementation complexity and power consumption. However, since the parent device does not know the wake-up schedule of its child devices, it may suffer from the idle listening problem. Polling message and corresponding ACK for every packet transmission may require large protocol overhead, which may noticeably degrade the transmission performance in the presence of CCI. Finally, polling message is vulnerable in the presence of contention and hidden-node collision, which may radically degrade the throughput in high-density WSNs.

3.2. IEEE 802.15.4 fixed frame structure

Synchronous MAC protocols such as IEEE 802.15.4 fixed frame structure (FFS) reduce the idle listening problem by means of duty-cycling. The FFS allows the coordinator and routers to use their own super-frames which are orthogonal to each other in time and frequency domain. Each super-frame starts with the transmission of a beacon frame. Child devices can make synchronization with their parent by receiving the beacon frame. The parent and its child devices only make transmission during a time interval, called active period, and stay in a sleep mode during the rest of time interval, called inactive period. By means of duty-cycling, the FFS can save power consumption. However, it cannot completely resolve the idle listening problem, since the active period remains unchanged even in the absence of signal to transmit or receive. The idle listening problem can be alleviated by making the active period (i.e., duty-cycle) very short. But this may lead to longer data transmission time.

Downlink transmission in the IEEE 802.15.4 FFS employs a pending method, where the pending field in the beacon frame specifies whether the parent device has data to send to its child devices. Child device which has receipt the beacon frame checks the pending field and sends data request message if its address is in the pending field. On the reception of the data request message, the parent device replies with ACK and transmit the downlink data. Since the data request message and corresponding ACK are required for every data packets, protocol overhead exists in the pending method (if the length of the data request message is the same as that of polling message, protocol overhead of the pending method is the same as that of the polling method). The pending method is more susceptible to the CCI than the polling method since the loss of the beacon frame results no data transmission in the whole active period, while the packet error rate (PER) is increased due to the protocol overhead associated with the data packet transmission.

4. Proposed transmission structure

In this chapter, we design a novel data transmission structure, referred to dynamic frame structure (DFS)) in a multi-hop WSN. From 4.1 to 4.3, we only consider single GW (i.e., single WSN) operation. In 4.4, we design a resource allocation algorithm for multi-GW operation. In 4.5, we consider an application of the designed DFS to IEEE 802.15.4e DSME. The concept of the proposed data transmission structure is illustrated in Fig. 4.1.

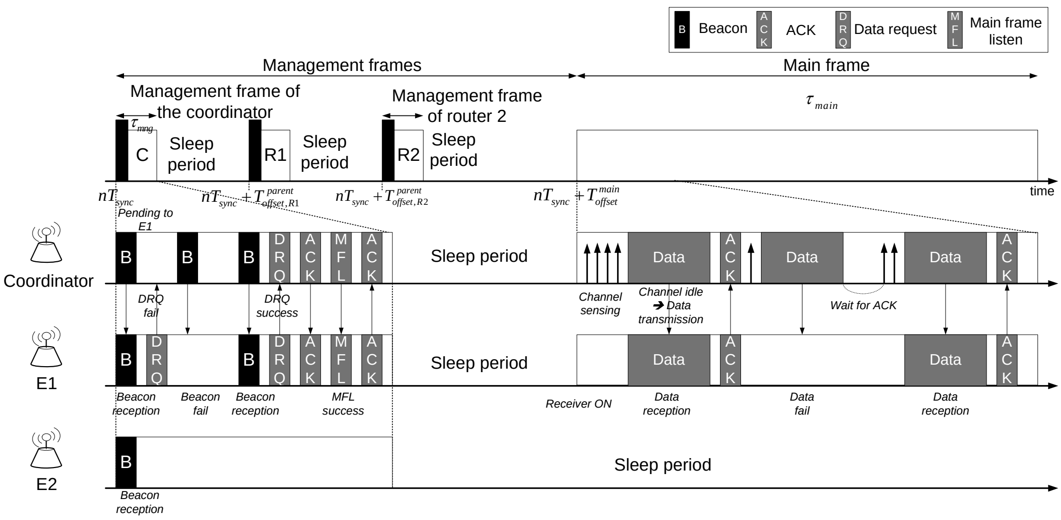


Fig. 4. 1. Concept of the proposed dynamic frame structure

4.1. Dynamic frame structure

We design a transmission frame structure which is composed of a management frame and a main frame as illustrated in Fig. 4.1. The management frame is used to exchange control messages to utilize the main frame and to maintain network connectivity. The main frame is used for downlink data transmission.

A parent device (e.g. the coordinator or router) periodically transmits a beacon frame at the beginning of its management frame and child devices (e.g., router or end device) periodically wake up to receive the beacon frame. Since multiple beacon frames may be transmitted in the presence of CCI, we call "the first beacon frame" the beacon frame which is first transmitted during each management frame.

Let T_{sync} be the beacon interval, $T_{offset,i}^{parent}$ be the time-offset between the time when the coordinator transmits the first beacon frame and the time when a parent device i transmits the first beacon frame, $T_{offset,i}^{child}$ be the time-offset between the time when the coordinator transmits the first beacon frame and the time when a child device i receives the first beacon frame transmitted by its parent device, and T_{offset}^{main} be the time-offset between the time when the coordinator transmits the first beacon frame and the time when the main frame begins during this beacon interval. Let τ_{mng} and τ_{main} be the duration of the management frame and the main frame, respectively. We assume that the coordinator transmits its first beacon frame at time $t = nT_{sync}$, where n is an integer.

As illustrated in Fig. 4.1, a parent device i transmits the first beacon frame at time $nT_{sync} + T_{offset,i}^{parent}$ and performs the management frame operation during τ_{mng}. A child device j wakes up at time $nT_{sync} + T_{offset,j}^{child} - GT$ and turns on its receiver to receive the beacon frame from its parent device, where GT denotes a guard time to compensate for clock drift. Receiving the beacon frame, it performs the management frame operation during τ_{mng}. Only a pair of devices (i.e., a parent and child device) who have applied for the use of main frame wake up at time $nT_{sync} + T_{offset}^{main}$ and perform the main frame operation during τ_{main}. The management frame and the main frame can be allocated separately in the time domain, by satisfying the following two inequalities as

$$\max_{i \in \{1,\cdots,K\}} \left\{ \max\left(T_{offset,i}^{parent}, T_{offset,i}^{child} \right) \right\} + \tau_{mng} \le T_{offset}^{main} \tag{4-1}$$

$$T_{offset}^{main} + \tau_{main} \le T_{sync} \tag{4-2}$$

where K indicates the number of devices in the network and $\max\{\cdot\}$ indicates the maximum number.

For brief overview of the proposed DFS, let us assume that the coordinator wants to send downlink data to its two-hop child C_2 via its one-hop child router C_1. The coordinator initially has a token for the use of main frame, referred to the main frame token. It sends a main frame listen (MFL) message to C_1 in the management frame. Upon receiving the MFL, C_1 decides to wake up in the next main frame to receive downlink data from the coordinator. In the next main frame, only the coordinator and C_1 wake up and perform the downlink data transmission. After sending all data to C_1, the coordinator sends a main frame handover (MFH) message to C_1 in the management frame, to handover the main frame token. Data can be transmitted from C_1 to C_2 using the same procedure used data transmission from the coordinator to C_1. After sending all data to C_2, C_1 sends an MFH to the coordinator in the management frame to return the main frame token. The detailed operation procedure of the management frame and the main frame is given in 4.1.1 and 4.1.2.

4.1.1. Management frame operation

The management frame is used to exchange control messages between the parent and its child devices. For reliable transaction of control messages, the proposed scheme considers repeated transmission of beacon frames.

Let I_{Main} be a binary flag indicating that a device has the main frame token as a parent (i.e., $I_{Main} = 1$, if it has the token). Let $I_{Activate}^{Parent}$ and $I_{Activate}^{Child}$ be binary flags indicating that a device has to handover the main frame token as a parent to its parent and child device, respectively. If it has to handover the main frame token, $I_{Activate}^{Parent} = 1$ or $I_{Activate}^{Child} = 1$.

As illustrated in Fig. 4.2, parent device i first checks out whether it has to transmit downlink control message. If $I_{Main} = 1$, it transmits an MFL to make its one-hop destination child device wake up during the main frame. If $I_{Activate}^{Child} = 1$, device i transmits an MFH to its child router to handover the main frame token.

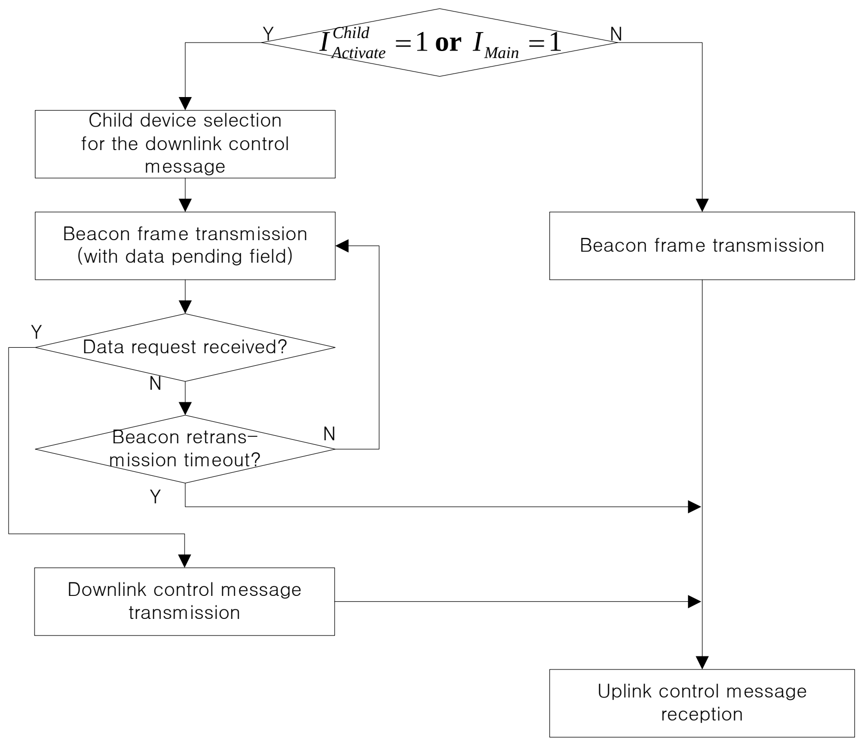


Fig. 4. 2. Parent procedure in the management frame of DFS

When a parent device i wants to transmit an MFL or MFH, it transmits a beacon frame with a data pending field at the beginning of the management frame. After the transmission of the beacon frame, device i waits for a data request message. If it does not receive the data request message during the ACK waiting time T_{ACK}, it retransmits the beacon frame during a duration of T_{RxOn}. After receiving the data request message, it transmits a downlink control message to the target node. Acknowledged beacon frame transmission greatly improves transmission reliability of the downlink control messages.

After transmitting the downlink control messages, device i turns on its receiver and waits for possible uplink control messages. If it received an MFH from one of its child routers, it sets the flag $I_{Main} \leftarrow 1$ (an MFH is not expected to be received if $I_{Main} = 1$ already). Other control messages for maintaining network connectivity may be transmitted, which is out of the scope of this thesis.

As illustrated in Fig. 4.3, a child device i first tries to receive the beacon frame during $GT + T_{RxOn}$. After receiving the beacon frame, it checks out the presence of data to be delivered. In the presence of data to be delivered, it sends a data request message and waits for a downlink control message from the parent. If another beacon frame is transmitted, this implies that the data request message was not successfully delivered to its parent. Then device i retransmits a data request message and waits for a downlink control message. After receiving the downlink control message, it sends an ACK to the parent. If the downlink control message is MFH, device i sets the flags, $I_{Activate}^{Child} \leftarrow 1$, $I_{Activate}^{Parent} \leftarrow 1$ and $I_{Main} \leftarrow 1$. If the downlink control message is MFL, it adjusts its timer so as to wake up at the beginning of the main frame. It transmits an uplink control message in the presence of data in the uplink. If $I_{Activate}^{Parent} = 1$, it transmits an MFH to its parent. Control messages for the maintenance of network connectivity can be transmitted.

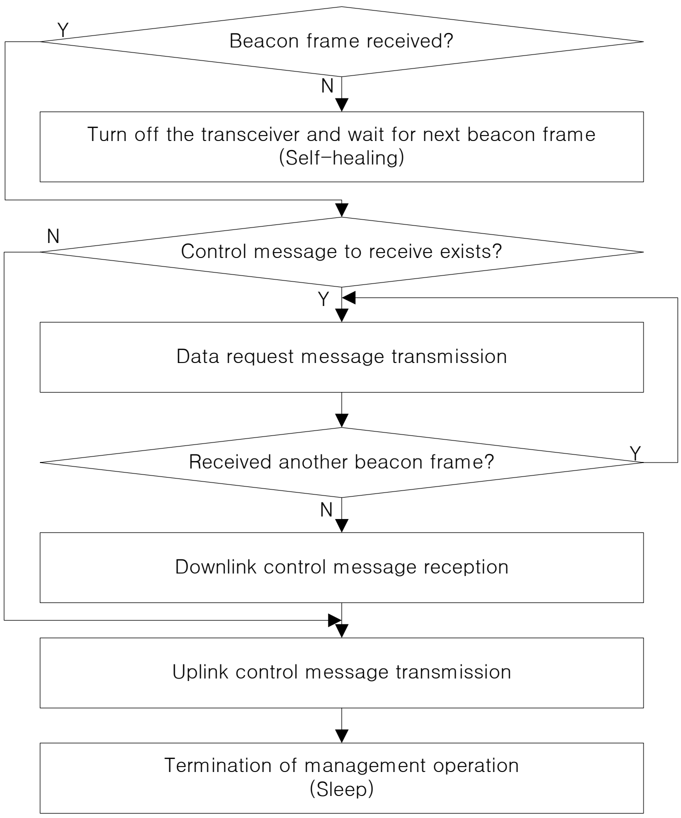


Fig. 4. 3. Child procedure in the management frame of DFS

The proposed management frame operation can provide arrangement for the main frame usage, management of the main frame token and reinforcement of the network connectivity. The management of the main frame token is quite applicable to multi-hop networks with scalability and the retransmission procedure of the beacon frame makes the DFS operation robust in error-prone environments (e.g., the presence of CCI).

4.1.2. Main frame operation

The main frame is used to transmit downlink data. Taking into consideration of the buffer size of the router, we can make the termination of the main frame usage and the

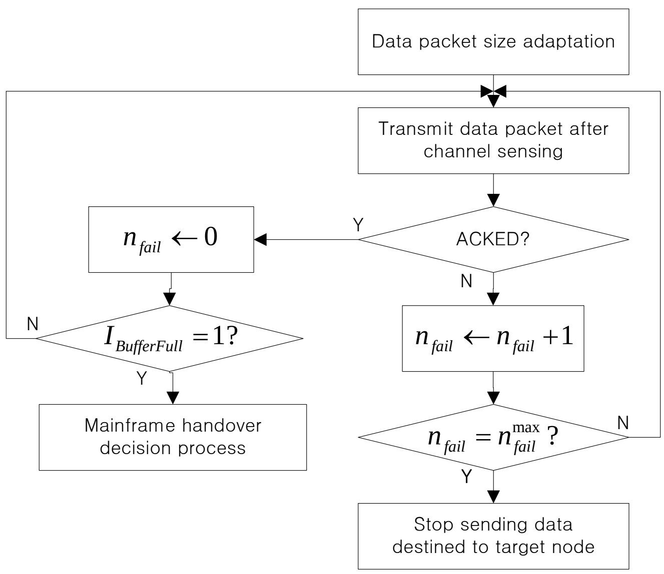


Fig. 4. 4. Parent procedure in the main frame of DFS

decision for the handover of the main frame token.

Let $I_{BufferFull}$ be a binary flag in the ACK message, indicating whether the buffer of the ACK sending device is full. If the buffer is full, $I_{BufferFull} = 1$. Let n_{fail} be the number of consecutive packet errors and $n_{fail}^{\max}$ be the maximum number of retransmissions.

The operation procedure of a parent device in the main frame is outlined in Fig. 4.4. Before the beginning of the main frame, the parent device adjusts the data packet size. At the beginning of the main frame, it performs channel sensing for an interval of $T_{Sensing}$. Then it transmits data packets after channel confirmation. The packet size adaptation and the downlink data transmission will be discussed in Section 4.2.

Receiving no ACK (i.e., ACK time out occurs), it updates $n_{fail} \leftarrow n_{fail} + 1$. If $n_{fail} < n_{fail}^{\max}$, it retransmits the data packet. If $n_{fail} = n_{fail}^{\max}$, it recognizes the failure of networking between itself and the target child device and stops data transmission. It defers data transmission by moving the data to the end of its buffer. On the other hand, receiving ACK, it resets $n_{fail} \leftarrow 0$ and checks out whether $I_{BufferFull} = 1$. If $I_{BufferFull} = 0$, it transmits the next data packet.

If $I_{BufferFull} = 1$, the device recognizes that the downlink data transmission to the target device is accomplished and goes into the mainframe handover decision process, which is summarized in Fig. 4.5.

The decision for mainframe handover is made taking into consideration of the buffer size, remaining data of the device and the network destination address. The parent device first checks out whether the network destination of the data is the target child device. If not, it adjusts flags $I_{Activate}^{Child} \leftarrow 1$ and $I_{Main} \leftarrow 0$ so that the main frame token can be transferred to the target child device. If the network destination of the data is the target device, it examines its buffer and if there are data, the device i does not update its information flags and terminates the main frame operation to serve data for the next child device in the next main frame. If there is no data, however, it makes $I_{Main} \leftarrow 0$ if it is the coordinator or makes $I_{Activate}^{Parent} \leftarrow 1$ and $I_{Main} \leftarrow 0$ if it is router device. $I_{Activate}^{Parent} \leftarrow 1$ is made so that the main frame token may return to its parent device.

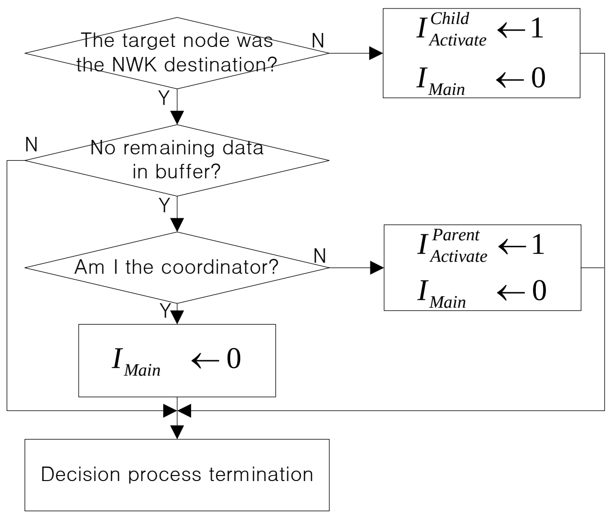


Fig. 4. 5. Mainframe handover decision process

The operation procedure of device i who works as child device in the main frame is illustrated in Fig. 4.6. The device i wakes up at the start of the main frame and turns its receiver on, waiting for data packets destined to it. If a data packet is received successfully, it replies with ACK. If its buffer is full, the ACK shall contain $I_{BufferFull} = 1$, $I_{BufferFull} = 0$ otherwise.

The proposed DFS reliably transmits downlink control messages in the management frame by transmitting multiple beacon frames if needed. The main frame handover process is well organized even in error-prone environments. Furthermore, only arranged devices wake up in the main frame, significantly alleviating the idle listening problem.

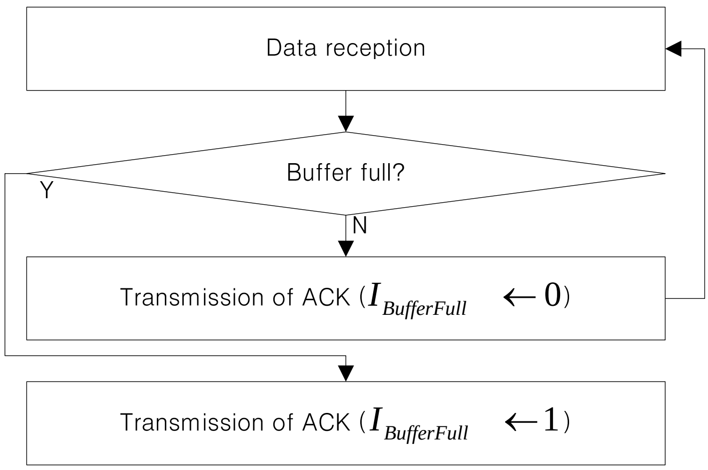


Fig. 4. 6. Child procedure in the main frame of DFS

4.2. Deferred data transmission

As mentioned in Section 4.1, the packet length is determined at the beginning of every main frame and the data transmission method in the DFS employs *deferred* data transmission, where channel sensing is performed before the data transmission. In this section, we describe the deferred data transmission method and the packet size adaptation scheme.

We describe the channel occupancy by WLAN using a two-state semi-Markov model, where the busy period of WLAN traffic lasts for a fixed time interval of T_w and the idle period follows with probability distribution function (PDF) $f_{T_I}(t_I)$ [4]. We assume that the idle period can be approximated as an exponential random variable with mean $E_T(t_I) = \lambda^{-1}$. Then, the channel occupancy ratio (or loading factor) of WLAN traffic can be defined by

$$\rho = \frac{T_w}{T_w + \lambda^{-1}},\ \rho \in [0,1). \tag{4-3}$$

Since no device in contending during the main frame, a simple ALOHA scheme with acknowledgement may be used to transmit downlink data. Then, the expected collision probability of data transmission in the presence of CCI can be represented as

$$p_{ALOHA}[c] = \rho\, p_{ALOHA}[c \mid \text{Busy}] + (1-\rho)\, p_{ALOHA}[c \mid \text{Idle}] \tag{4-4}$$

where $p_{ALOHA}[c \mid \text{Busy}]$ and $p_{ALOHA}[c \mid \text{Idle}]$ denotes the collision probability when the transmitter attempts to transmit data in the presence and absence of CCI, respectively. $p_{ALOHA}\left[c\,|\,\text{Idle}\right]$ can be represented as

$$p_{ALOHA}\left[c\,|\,\text{Idle}\right]=1-\exp\left\{-\lambda\frac{\left(L_{Data}+L_{ACK}\right)}{R_{data}}\right\} \tag{4-5}$$

where L_{Data} and L_{ACK} denotes length of data packet and ACK, respectively, and R_{Data} is the data rate. Since $p_{ALOHA}\left[c\,|\,\text{Busy}\right]=1$, the expected collision probability can be rewritten as

$$p_{ALOHA}\left[c\right]=1-\left(1-\rho\right)\exp\left\{-\lambda\frac{\left(L_{Data}+L_{ACK}\right)}{R_{data}}\right\}. \tag{4-6}$$

Conventional indirect transmission method discussed in Section 3.3 employs a four-way handshake protocol, comprising Data request(U)-ACK(D)-Data(D)-ACK(U). Assuming that the channel detection probability is 1, data transmission begins when the channel is idle. Then, the collision probability can be represented as

$$p_{FFS}\left[c\right]=1-\exp\left\{-\lambda\frac{\left(L_{DataReq}+L_{Data}+2L_{ACK}\right)}{R_{data}}\right\} \tag{4-7}$$

where $L_{DataReq}$ denotes the length of the data request message. If the length of the polling message is equal to the data request, the collision probability of polling method discussed in Section 3.1 equals (4-7). It can be seen that the increased protocol overhead for the data request message and corresponding ACK leads to performance degradation in the presence of CCI.

The proposed deferred data transmission method reduces protocol overhead by removing the nonfunctional data request and corresponding ACK . Furthermore, the proposed scheme adopts channel sensing before the data transmission, leading to the collision probability represented as [5]

$$p_{DFS}\left[c\right]=1-\exp\left\{-\lambda\frac{\left(L_{Data}+L_{ACK}\right)}{R_{data}}\right\}. \qquad (4\text{-}8)$$

The simulation and analysis result is shown in Fig. 4.7. It can be seen that the proposed scheme achieves lowest collision probability, which may lead to faster data transmission and better power efficiency.

Eq. (4-8) implies that short packet leads to small collision probability. However, since the length of overheads including header and ACK is fixed, the effect of the overheads increases as the packet length is shortened. Therefore, there is an optimal packet length which leads to maximum throughput, as shown in Fig. 4.8. However, to calculate the optimal packet length, it is needed to estimate the channel occupancy ratio of CCI signals. The channel occupancy ratio may be estimated in idle period of DFS system, but the energy consumption due to channel sensing may be large. Thus we propose a simple algorithm which uses the number of retransmission of beacon frames in the managements frame as a criterion. If there was no retransmission of beacon frames, the parent device determines packet length as L_1 which achieves the best throughput when $\rho = 0.1$ (low channel occupancy ratio) and if there was retransmission of beacon frames, the parent device chooses packet length L_2 which achieves the best throughput when $\rho = 0.3$ (high channel occupancy ratio).

With the deferred data transmission method and the packet size adaptation, the proposed scheme provides robust data transmission in error-prone environments.

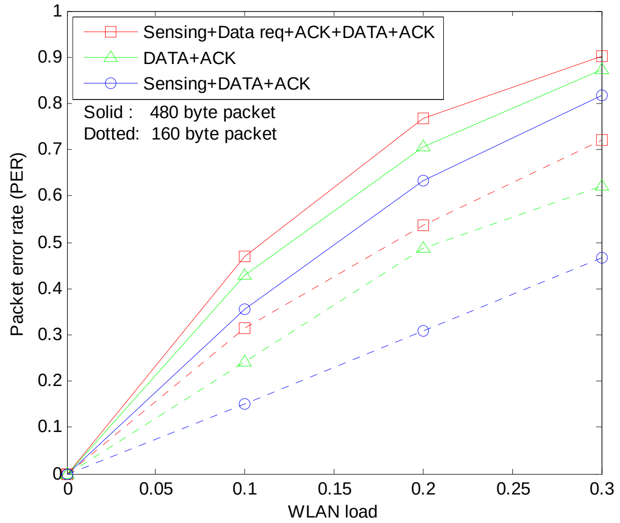


Fig. 4. 7. Packet error rate due to WLAN load

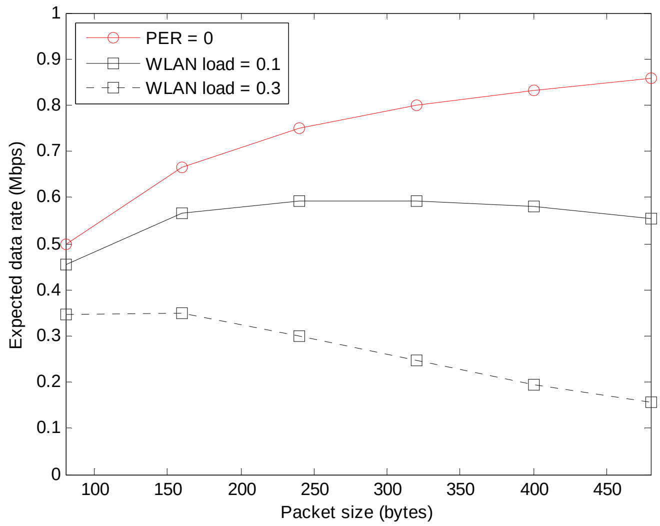


Fig. 4. 8. Expected data rate due to packet size when deferred transmission is applied

4.3. Multi-gateway operation

In this section, we will discuss a resource allocation scheme for multi-GW operation, summarized in Fig. 4.9. For seamless application of single-GW protocols discussed in Section 4.1 and Section 4.2, we consider to allocate different channel to adjacent GWs. If a new GW requests to join, the server allocates a channel if available. If there is no vacant channel, i.e. more than N_{ch} GWs are managed by the server, the server makes the GW scan channels being used by adjacent GWs. Here N_{ch} denotes number of channels may be used (e.g. for IEEE 802.15.4, $N_{ch} = 16$ in 2.4 GHz band). Then, the GW collects information of channel usage throughout its network. When the GW reports the channel usage information, the server allocates a channel appropriate for the GW. By this way, spatial reuse of the frequency resource may be achieved.

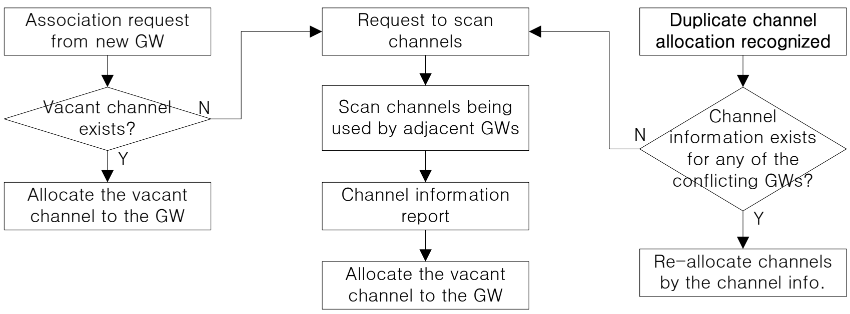


Fig. 4. 9. Resource allocation algorithm for multi-GW operation

However, there may be so-called hidden-node situation between the new GW and other adjacent GWs where the devices in the network of the new GW cannot hear beacon frames from adjacent GWs. An example of this situation is depicted in Fig 4.10. In this figure, the red marks and blue marks denotes devices in the pre-existing network and devices in the network of the new GW, respectively. Stars denote GWs, squares denote routers and circles denote end devices. Since any signal from the coordinator or routers in the pre-existing network are not heard by the devices of the new network, the new GW may consider the channel of the pre-existing network vacant. Since the server may not have geological information of GWs, duplicate

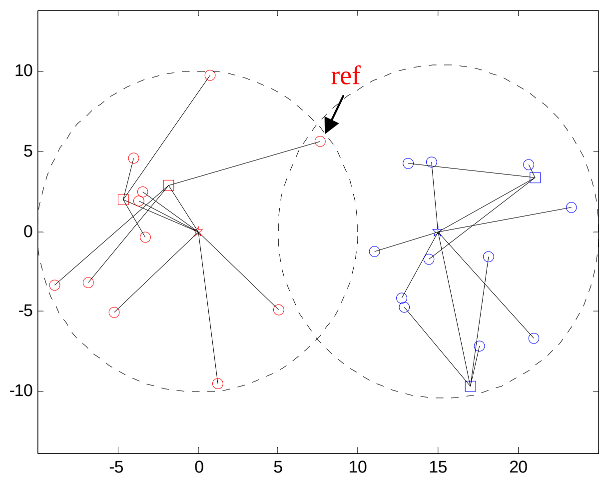


Fig. 4. 10. An example of hidden-node situation

allocation of channel may occur. In this situation, the network connectivity may not persist due to direct beacon collision. In the Fig. 4.10, a device denoted as “ref ” may suffer from the aforementioned direct beacon collision. To alleviate this problem, we added a stage of collecting the channel usage information during the self-healing process. When the direct beacon collision occurs and an orphan device is generated, the orphaned device broadcasts an orphan indication message. On the reception of the message, coordinators or routers adjacent to the node replies with their channel information. During this stage, the orphaned device may distinguish direct beacon collision from other network failure (e.g. battery-exhaustion of parent device, link-loss by CCI). When the direct beacon collision is recognized, the orphaned device reports the situation to the GW which it is belong to and the GW re-associates with the server so as to be allocated an appropriate channel.

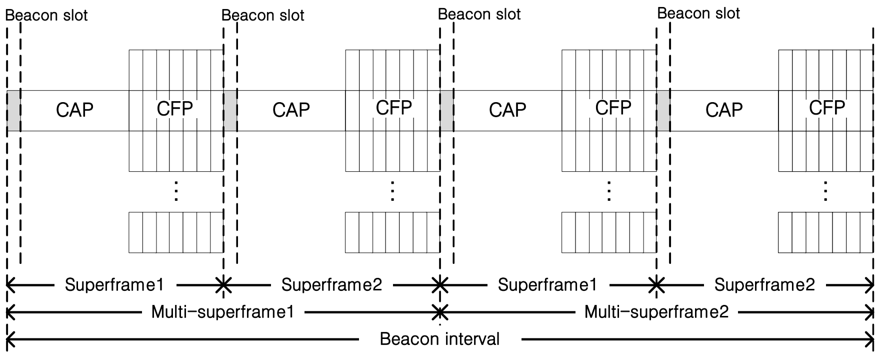
4.4. DFS applied on IEEE 802.15.4e DSME

IEEE 802.15.4 (revised in 2006) is a standard that has attractive features such as low energy consumption by duty-cycling and a simple random channel access (CSMA/CA). CSMA/CA is robust to large variations in traffic but the random behavior of CSMA/CA makes it difficult to deliver real-time traffic and large volume of data [6-7]. Other channel access scheme, time-division multiple access (TDMA), is also available in IEEE 802.15.4 but the static feature of TDMA and complexity of resource scheduling prohibited TDMA mechanism in IEEE 802.15.4 from wide-acceptance [8]. IEEE 802.15.4 WSNs operating over the 2.4-GHz Industrial, Scientific, and Medical (ISM) band share the radio frequency (RF) band with WLAN, Bluetooth, etc. A number of literatures reported that IEEE 802.15.4 is vulnerable to CCI due to its single-channel operation [9-10].

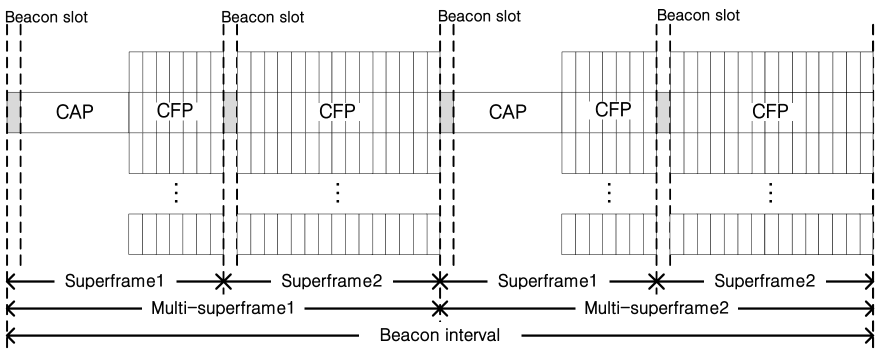
Recently, IEEE 802.15 TG4e amended IEEE 802.15.4 MAC specifications to enhance RF link reliability and guarantee determinism on channel access. Deterministic and synchronous multi-channel extension (DSME) MAC protocol is included as a core MAC operation mode in IEEE 802.15.4e (2012) [11]. DSME encapsulates multi-channel operation via channel adaptation or channel hopping to achieve channel diversity gain. DSME also makes it possible to transmit real-time traffic or large amounts of data by increased number of time slots and peer-to-peer TDMA resource allocation. Recent studies evaluated the performance of DSME in variant environments [12-13].

We found that the deterministic channel access feature (e.g. main frame usage) and synchronous operation feature of proposed DFS are similar to DSME. In this section, we propose an application of DFS on IEEE 802.15.4e, expecting faster mercerization of DFS.

Frame structure of DSME is depicted in figure 4.11. A coordinator or a router sends a beacon frame in one of beacon slots in the beacon interval. All devices shares contention access period (CAP) and transmits signals by means of CSMA/CA. Only scheduled devices uses enhanced guaranteed time slots (EGTS) in contention free period (CFP). Since EGTSs are guaranteed to a pair of devices, signals are directly



(a) CAP reduction disabled



(b) CAP reduction enabled

Fig. 4. 11. Frame structure of DSME

transmitted with no channel sensing or other contention mitigating mechanism. The superframe duration (SD), multi-superframe duration (MD) and beacon interval (BI) are given as

$$SD = aBSD \times 2^{SO}, \tag{4-9}$$

$$MD = aBSD \times 2^{MO}, \tag{4-10}$$

$$BI = aBSD \times 2^{BO}, \tag{4-11}$$

where $aBSD$ denotes a constant called *aBaseSuperframeDuration* (15.36 ms) and SO, MO and BO denotes superframe order, multi-superframe order and beacon order, respectively ($0 \le SO \le MO \le BO \le 14$).

To use EGTSs, a 3-way scheduling mechanism is used, namely EGTS request, EGTS reply and EGTS notification. A device which want to use EGTS first sends EGTS request to the target device. The target device replies the success or failure with EGTS reply. If the EGTS request is accepted, the source device broadcasts a EGTS notify message to neighbor devices. To track with current state of channel allocation, all devices must wake up at all CAPs and overhear EGTS command messages. EGTS reply and EGTS notify contain channel bitmap for other device to update channel allocation state.

CAP reduction mode is available to extend TDMA operation, thus the throughput may be increased. Number of EGTSs is 7 if CAP reduction is disabled. If CAP reduction is enabled, only the first superframe of a multi-superframe has CAP (7 EGTSs) and other superframes have no CAP (15 EGTSs).

We propose a slight variation of DSME to accommodate downlink application of large volume data. First, we enable CAP reduction option to maximize data transmission period. Devices who work as parents (coordinators or routers) transmit beacon signals at the start of each multi-superframes. To satisfy this condition, 2^{BO-MO} must be larger than or equal to the number of parent devices. Since data transmission occurs on only a pair of devices, the devices do not need to wake up during all the CAPs. Instead, a child device only wake up at the CAP which follows right after the transmission of beacon signal from its parent device. In other words, the CAP works as a management frame of the proposed DFS. By this way, the duty-cycle when the data transmission is not performed can be decreased to $\frac{7}{16}2^{SO-BO}$ from $\frac{7}{16}2^{SO-MO}$. The CFP works as a main frame of the DFS, i.e. the CFP can be thought as the main frame of DFS scattered into whole beacon interval. The authority of the usage of main frame is now substituted to the authority of EGTS scheduling. A parent device who has the authority of EGTS scheduling may schedule EGTS to transmit downlink data. The scheduling process may be directly adopted from conventional DSME.

To reinforce the reliability of transmission of downlink command messages, the repeated transmission of beacon frames scheme may be applied. Channel hopping mechanism specified in the DSME also may be used to mitigate CCI. An example of operation of proposed DFS-DSME in a simple line topology is illustrated in the Fig. 4.12.

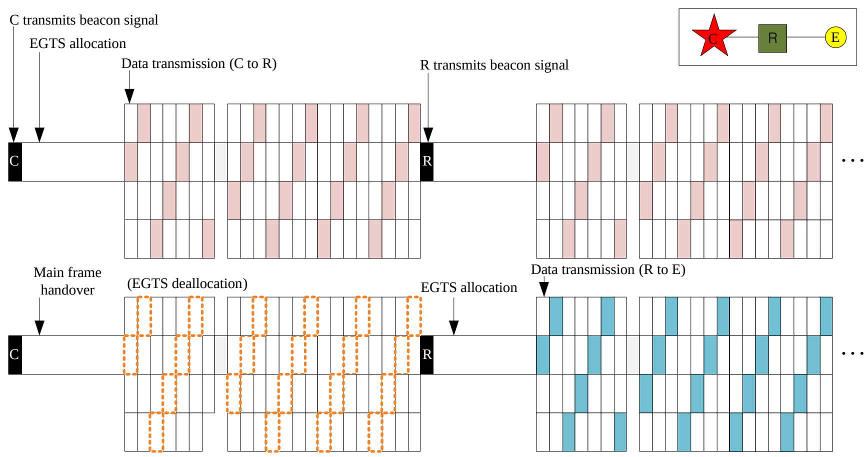


Fig. 4. 12. An example of data transmission of DFS applied on DSME

5. Performance evaluation

The performance of the proposed DFS is verified by computer simulation. The simulation environment is summarized in Table I, which considers the operation of a

Table. 4. 1. Simulation parameter

Simulation parameters	Values
T_{sync}	983.04 ms
τ_{mng}	15.36 ms
τ_{main}	491.52 ms
Number of devices	500
NWK topology	Cluster-tree (3-hop with 7 routers)
Data size per device	15 kB
Buffer size	15 kB
Data rate	250 kbps (IEEE 802.15.4 PHY)
WLAN idle time duration	Exponential distribution
WLAN busy time duration (T_w)	1 ms
(L_1, L_2)	(60 bytes, 40 bytes)

multi-hop wireless sensor network. For comparison, we also evaluate the performance of polling and IEEE 802.15.4 FFS.

For fair comparison, we assumed that the time when the polling message is transmitted is ideally distributed in the polling scheme. That is, just one device polls its parent device just after the data transaction with another device is terminated, which implies that there is no contention or hidden-node collision.

Furthermore, we set the parameters of IEEE 802.15.4 FFS so that it achieves best performance in the sense of data transaction time. Since there are only 7 routers in the network, we have set $BO = 6$ and $SO = 3$ (1/8 duty-cycle).

Since the length of data packet greatly affects the performance of the system in the presence of the CCI, we evaluated the polling scheme and the IEEE 802.15.4 FFS with 2 different packet lengths, namely 120 bytes and 40 bytes.

Fig. 5.1 illustrates the total data transmission time due to WLAN load. For IEEE 802.15.4 DFS and the ideal polling, the solid and dotted line denotes that the packet length is 40 bytes and 120 bytes, respectively. While DFS uses 50 % of time to transmit data $\left(\tau_{main}/T_{sync} = 0.5\right)$, the ideal polling uses 100% of time to transmit data, exhibiting better performance in low WLAN load. However, as the channel occupancy ratio of WLAN increases, the packet collision rate abruptly increases in the ideal polling, showing even longer data dissemination time. IEEE 802.15.4 FFS shows worse performance than the packet collision rate discussed in Section 4.2, due

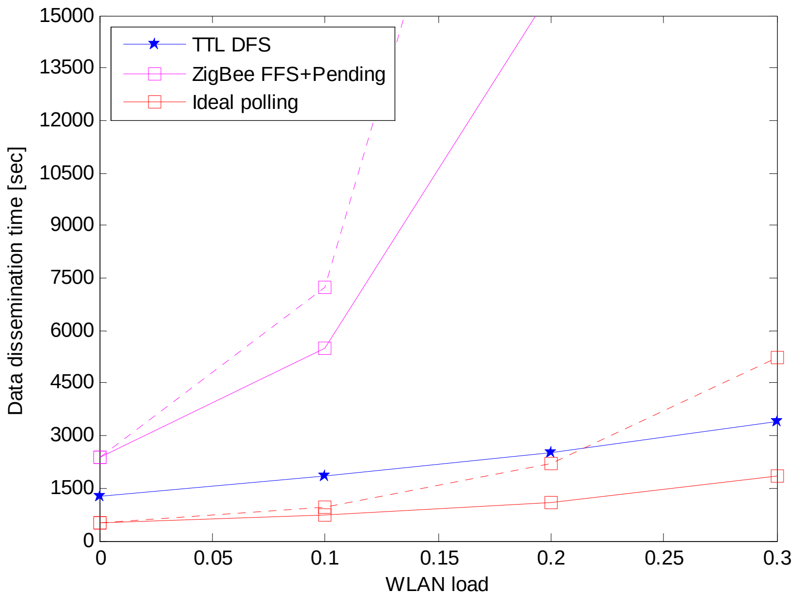


Fig. 5. 1. Data dissemination time due to WLAN load

to two-fold effect of beacon loss and data packet collision. Proposed DFS greatly shortens the data dissemination time than the FFS using repeated beacon transmission and deferred data transmission scheme. Furthermore, the FFS may use 1/8 (data transmission of GW to its child) to 1/4 (data transmission of GW to its child and that of a router to its child simultaneously) of time for the data transmission, while the proposed DFS may utilize 50% of time by the main frame handover algorithm, reducing the waste of time compared to the FFS.

Fig. 5.2 depicts the energy consumption during the data dissemination time due to WLAN load when the packet length is 40 bytes. The solid line denotes the average

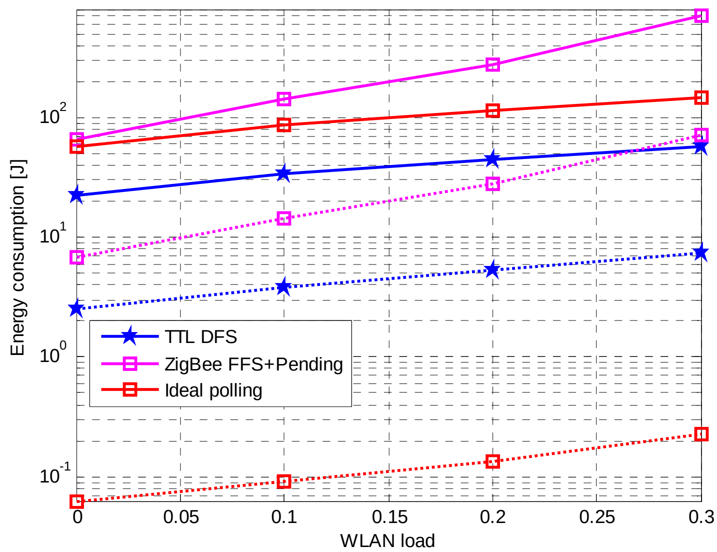


Fig. 5. 2. Data dissemination time due to WLAN load

energy consumption of routers and the dotted line denotes the average energy consumption of end devices. It can be seen that the router consumes 10 times of the energy than the end device in the proposed DFS and the FFS. However, in the ideal polling, the router consumes much more energy than the end device since they must be always ON as discussed in Section 3.1. The proposed DFS shows lowest energy consumption by reducing the idle listening time.

6. Conclusion

In this thesis, we have considered a downlink data transmission structure for high density and large scale multi-hop wireless sensor networks. We first have proposed a dynamic frame structure (DFS) where a management frame and a main frame repeat in every beacon interval. In the management frame, parent and child devices transmit and receive the control message to maintain the network connectivity and to utilize the main frame. In the main frame, only pair of a parent device and a child device transmit/receive data packets while the other devices sleep to minimize power consumption. Proposed DFS provides reliable transmission of control messages even if co-channel interference (CCI) exists by repeated transmission of beacon frames and data request messages. DFS achieves high data transmission in the CCI environments by selecting appropriate packet length and deferred transmission of data packets. We further investigated the resource allocation scheme for multiple GWs and the application of DFS to the IEEE 802.15.4e DSME. The simulation results have verified that the proposed scheme shows better energy efficiency while the data dissemination time is greatly reduced.

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초 록

본 논문은 하나의 코디네이터(coordinator)가 다수의 단말기기들과 하나 이상의 홉(hop)으로 연결되어 구성된 무선 통신 시스템에서 하향 링크 (downlink) 데이터를 전송하는 방법에 관한 것이다. 본 논문은 먼저 매 비컨 간격마다 관리 프레임(management frame)과 주 프레임(main frame)이 반복되는 유동 슈퍼프레임 구조(dynamic frame structure: 이하 DFS)를 정의한다. 상기 관리 프레임에서는 네트워크 관리에 필요한 제어 메시지(control message)를 송/수신 하며, 상기 주 프레임에서는 데이터를 주고 받는 부모-자녀 기기 쌍 만이 데이터를 송/수신 하고, 다른 기기들은 송수신기 동작을 중지 하여 전력 소모를 최소화한다. 한편 DFS 는 관리 프레임에서 비컨 신호 및 데이터 요청 메시지 반복 전송을 통하여 제어 메시지 전송의 신뢰성을 높이고, 주 프레임에서 알맞은 패킷 길이를 설정하고 채널을 센싱한 후 채널이 유휴할 경우에만 데이터 전송을 시작함으로써 간섭 환경에서 데이터 전송 성능을 향상시킬 수 있다. 또한 본 논문은 DFS 에서 다중 게이트웨이(gateway)가 동작할 수 있는 방법을 제시하며 DFS 를 IEEE 802.15.4e 표준에 적용하는 방법 또한 검토한다.

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