M. S. Thesis

Packet Collision Alleviation in IEEE 802.15.4 Networks

IEEE 802.15.4 네트워크에서의 패킷 충돌 완화 기법

August 2013

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이 論文을 工學碩士學位論文으로 提出함

2013 年 8 月

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金泰勳의 工學碩士學位論文을 認准함

2013 年 8 月

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Abstract

Recently, IEEE 802.15.4 has been considered as an efficient candidate for wireless sensor networks that require low-complexity and low-power features. Child devices transmit packets to the coordinator by means of carrier sense multiple access with collision avoidance (CSMA/CA) with low message overhead. However, they may experience severe packet collision when a number of child devices transmit large number of data packets, yielding low transmission performance. Therefore, it may be desirable to alleviate packet collision to enhance the transmission performance.

The CSMA/CA mechanism may suffer from two types of packet collision; contention collision and hidden node collision. The contention collision problem may occur in CSMA/CA-based packet transmission. When devices perform channel sensing at the same time, they may have opportunities of transmitting data packets simultaneously. In a CSMA/CA-based multi-user communication system, the contention collision problem is unavoidable and can be worse as the number of contending devices increases. The hidden node collision problem may occur when a device cannot detect the packet transmission of other devices. As a consequence, the device determines that channel is idle and initiates its own packet transmission, causing packet collision. It is experimentally known that a pair of devices may be in a hidden node relationship at a probability of up to approximately 41%. Although IEEE 802.15.4 networks may severely suffer from these packet collisions, it does not provide a mechanism to alleviate these collision problems.

In this thesis, we consider the design of a novel scheme that can reduce packet collisions without high message signaling overhead. To this end, we partition the transmission period (e.g., the active period in IEEE 802.15.4 networks) into a number of periods each of which is allocated to a small number of child devices, reducing the contention collision. We can alleviate the hidden node problem by making child devices in a hidden node relationship use different transmission periods. Finally, the performance of the proposed scheme is verified by computer simulation in terms of the aggregated throughput and energy efficiency in contention-based transmission environments.

Keywords: IEEE 802.15.4, CSMA/CA, Packet collision, Partitioning

Student number: 2011-20822

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1. Introduction

IEEE 802.15.4 is a standardized specification for low-rate wireless personal area networks (WPANs) operating in the 2.4 GHz industrial, scientific and medical (ISM) spectrum band [1]. It has been considered as one of efficient communication protocols applicable to wireless sensor networks due to the nature of low-power and low-complexity features. It employs a medium access control (MAC) based on carrier sense multiple access with collision avoidance (CSMA/CA) which can incorporate with energy saving features [2, 3]. Child devices can reduce power consumption in packet transmission by means of carrier sensing with a random back-off delay. In addition to the power saving feature, IEEE 802.15.4 employs a so-called binary exponential back-off (BEB) mechanism to alleviate the packet collision problem. However, it may still suffer from packet collision, mainly associated with contention collision and hidden node collision. Both the collisions occur frequently in normal operation environment and deteriorate the transmission performance. However, IEEE 802.15.4 does not provide a mechanism to alleviate them.

The contention collision problem may occur in CSMA/CA-based packet transmission. When devices perform channel sensing at the same time, they may not recognize the channel occupancy. As a consequence, they may have opportunities of transmitting data packets simultaneously. In a CSMA/CA-based multi-user communication system, the contention collision problem is unavoidable and can be worse as the number of contending devices increases.

IEEE 802.15.4 considered the BEB mechanism to alleviate contention collision by reducing the chance of simultaneous packet transmission. When a contention collision occurs, devices double the maximum back-off period and randomly choose a back-off period between zero and the maximum back-off period. However, this mechanism may cause serious wastage of resource in low traffic environments and may not alleviate contention collision in high traffic environments, yielding significant performance degradation.

To alleviate the contention collision, previous works considered the change of MAC parameters [4, 5]. They showed that the back-off mechanism in IEEE 802.15.4 cannot well reflect the degree of contention and try to adjust back-off period more well-reflecting the degree of contention. The MAC parameters (e.g., the back-off period) can be adjusted in consideration of the operation environment and history of packet transmission. The MAC parameters are not reset after packet transmission unlike the IEEE 802.15.4, enabling to maintain valid back-off period to avoid contention collision. However, the adjustment of MAC parameters may not be efficient in time-varying operation environments when performed in a fixed transmission period structure. Moreover, when the range of MAC parameters is predetermined, the adjustment of MAC parameters may yield marginal performance improvement. In time-varying operation environments, the transmission period can be partitioned into a fixed number of periods to alleviate the contention collision problem, referred to operation partition [6]. It allocates each device its operation period during the network association process. However, the use of fixed partitioning still may not be effective in time-varying operation environments, yielding resource wastage similar in IEEE 802.15.4.

To reduce contention collisions in IEEE 802.15.4 based networks, we consider adaptive partitioning of the transmission period according to network operation environments. The proposed scheme make the network coordinator and its child devices measure the transmission performance in a distributed manner. When the measured performance is not satisfactory, the coordinator adjusts the number of partitions according to the operation environment. Each child device can determine its transmission period for its packet transmission by itself without control by the network coordinator. The simulation results show that the proposed partitioning scheme can remarkably reduce the failure rate and energy consumption, while guaranteeing the throughput performance.

The hidden node collision problem may occur when a device cannot detect the packet transmission of other devices. As a consequence, the device determines that channel is idle and initiates its own packet transmission, causing packet collision. . It is experimentally known that a pair of devices may be in a hidden node relationship at a probability of up to approximately 41% [7]. However, IEEE 802.15.4 provides no mechanism to alleviate hidden node collisions. Previous works considered node grouping methods to alleviate the hidden node collision problem [7, 8]. Each group comprises child devices not in hidden node relationship and uses different resources for the packet transmission. Hidden node relationship between end devices is examined during a hidden node recognition period. During hidden node recognition period, the coordinator uses a polling mechanism for the examination. For example, the coordinator transmits a polling message to one target child device and the child device transmits a data request message. Other end devices try to overhear the data request message, recognizing whether they are in hidden node relationship with the target device. Devices who are in hidden node relationship with target device report the hidden node relationship to coordinator. The coordinator repeats these processes for every end device. After the recognition, the coordinator allocates different time-division multiple access (TDMA)-based transmission period to end devices who are in hidden node relationship. These grouping methods may efficiently alleviate the hidden node problem at the expense of long recognition period, which may require large energy consumption and no packet transaction. Moreover, the allocation of TDMA-based transmission period may requires an efficient scheduling algorithm, which may increase processing overhead.

We consider the alleviation of the hidden node problem. To this end, we employ a pending mechanism in IEEE 802.15.4, which can recognize hidden node relationship between end devices, and a partitioning method to allocate orthogonal resource to end devices in hidden node relationship. The coordinator first detects hidden node collision and the source address of collided packets. It detects the hidden node relationship using a pending mechanism and allocates child devices in hidden node relationship the transmission period differently. In this manner, hidden node collision may be remarkably reduced. Additionally, the proposed scheme does not require additional hidden node recognition period and adopts the pending mechanism in IEEE 802.15.4 for hidden relationship recognition during normal operation, considerably reducing additional message overhead and guaranteeing compatibility with IEEE 802.15.4.

The remainder of this thesis is organized as follows. Chapter II describes the system model considered in this thesis. Chapter III briefly reviews previous works for the alleviation of packet collisions. Chapter IV describes the proposed schemes and evaluates them by computer simulation. Finally, Chapter V concludes this thesis.

2. System model

Consider the operation of an IEEE 802.15.4 network with a cluster tree-topology structure, which is composed of the network coordinator and K child devices. As illustrated in Fig. 2.1, the beacon-enabled IEEE 802.15.4 network operates using a periodic super-frame structure comprising active and inactive period. The network coordinator periodically transmits the beacon frame for network synchronization before the beginning of the active period. Receiving a beacon frame, the child devices can make communications with the network coordinator by means of slotted CSMA/CA during the active period and stay in an idle mode during the inactive

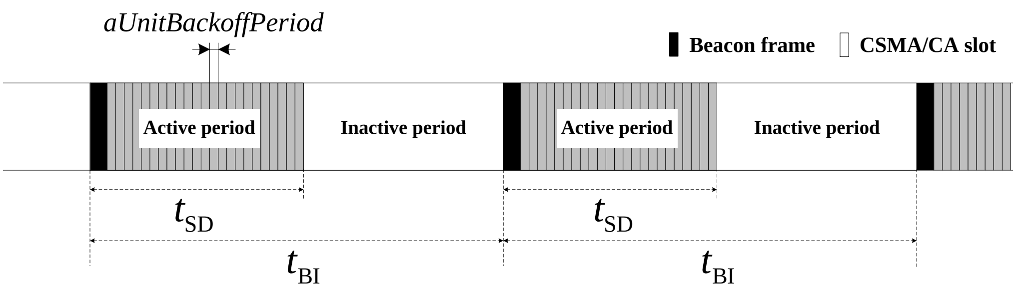

Fig. 2. 1. The super-frame structure in the IEEE 802.15.4 beacon-enabled mode

period. The beacon interval and the super-frame duration are determined as, respectively,

$$t_{\mathrm{BI}} = \left(aBaseSuperframeDuration \cdot 2^{BO}\right) t_{\mathrm{sym}}, \quad \text{for } 0 \le BO \le 14 \tag{2-1}$$

$$t_{\mathrm{SD}} = \left(aBaseSuperframeDuration \cdot 2^{SO}\right) t_{\mathrm{sym}}, \quad \text{for } 0 \le SO \le BO \tag{2-2}$$

where BO is the beacon order, SO is the super-frame order and t_{sym} is the symbol time. The slotted CSMA/CA mechanism operates in a unit of *aUnitBackoffPeriod* [1].

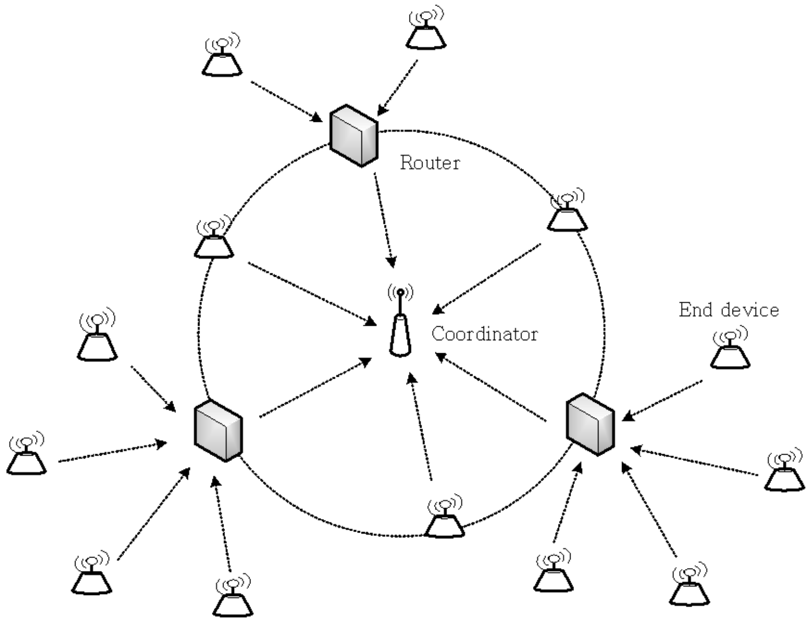

Fig. 2. 2. Example of sensor device deployment

As depicted in fig 2.2, we consider uplink data transmissions using CSMA/CA mechanism. The coordinator plays the role as so-called sink, accumulating packets from child devices. Router relays uplink data packets from end devices to the coordinator.

When energy detection-based channel sensing detector is employed with simple hypothesis testing, it can make a decision on clear channel as

$$D = \begin{cases} H_1; & \text{if } \sum_{j=n-N+1}^{n} |r(j)|^2 \geq N\lambda \\ H_0; & \text{otherwise} \end{cases} \tag{2-3}$$

where H_0 and H_1 denote hypothesis corresponding to the absence and the presence of interference signal in the channel, respectively, r denotes the received signal, N is the number of samples for the test, and λ is a detection threshold to be determined.

3. Previous works

3.1. Backoff algorithm in slotted CSMA/CA

IEEE 802.15.4 MAC adopts low-power CSMA/CA to support competition-based packet transmission. The child device attempting to transmit packets first performs channel sensing, referred to the clear channel assessment (CCA), after a random back-off delay. It transmits packets only when the channel is clear. When the channel is busy, the child device exponentially increases the maximum back-off delay to reduce the contention. However, it may suffer from the wastage of resource in low traffic environments and severe contention collision in high traffic environments.

The packet transmission failure rate R_{f} and the resource utilization ratio R_{u} can be represented as, respectively,

$$R_{\mathrm{f}} = \frac{x^{m+1}\left(1-y^{n+1}\right)}{1-y} + y^{n+1} \tag{3-4}$$

$$R_{\mathrm{u}} = L_{\mathrm{succ}}^{\mathrm{UBP}} K p_{\mathrm{CCA}} \left(1-p_{\mathrm{CCA}}\right)^{K} (1-\alpha)(1-\beta) \tag{3-2}$$

where x and y are respectively the probability of performing the back-off process due to the presence of busy channel and packet collision, m and n are respectively the probability of performing the back-off process with *macMaxCSMABackoffs* and *macMaxBackoffRetries*, α and β are respectively the probability that the channel is declared as a busy channel through the first and the second CCA, $L_{\text{succ}}^{\text{UBP}}$ is the length of the transmitted packet with a unit of *aUnitBackoffPeriod*, and p_{CCA} is the probability that the child device performs the CCA. The total energy consumption E_{tot} per *aUnitBackoffPeriod* can be represented as

$$\begin{aligned} E_{\text{tot}} = K\left(320\times10^{-6}\right)\Bigg[\frac{P_{\text{idle}}\,p_{\text{CCA}}}{2}\left\{\frac{(1-x)\left(1-(2x)^{m+1}\right)}{(1-2x)\left(1-x^{m+1}\right)}2^{macMinBE}-1\right\}+P_{\text{CCA}}\,p_{\text{CCA}}\,(2-\alpha) \\ +(1-\alpha)(1-\beta)\,p_{\text{CCA}}\left\{\bar{n}_{\text{succ}}^{\text{UBP}}P_{\text{tx}}+P_{\text{idle}}+\left(P_{\text{rx}}\left(1-p_{\text{c}}\right)+P_{\text{idle}}\,p_{\text{c}}\right)\right\}\Bigg] \end{aligned} \tag{3-3}$$

where $P_{\text{idle}}, P_{\text{CCA}}, P_{\text{tx}}$ and P_{rx} are the power consumption in the idle state, channel sensing, transmission and reception mode, respectively.

3.2. Previous contention collision alleviation schemes

To alleviate the contention collision problem, enhanced collision alleviation method(ECAM) is proposed. The ECAM divides the transmission period into two sub-transmission periods and informs the child devices which transmission period will be used for the network association process, reducing the contention by one half. However, it may not be effective in time-varying operation environment as in the

802.15.4 MAC[6].

If the transmission period is equally partitioned into n_p sub-transmission periods, the transmission failure rate and the resource utilization ratio can be represented as, respectively,

$$R_{\mathrm{f}}^{(n_p)} = \frac{x^{(n_p)\,m+1}\left(1-y^{(n_p)\,n+1}\right)}{1-y^{(n_p)}} + y^{(n_p)\,n+1} \tag{3-4}$$

$$R_{\mathrm{u}}^{(n_p)} = \bar{n}_{\mathrm{succ}}^{\mathrm{UBP}} \frac{K}{n_p} p_{\mathrm{CCA}}{}^{(n_p)}\left(1-p_{\mathrm{CCA}}{}^{(n_p)}\right)^{K/n_p}\left(1-\alpha^{(n_p)}\right)\left(1-\beta^{(n_p)}\right). \tag{3-5}$$

The total energy consumption can be represented as

$$\begin{aligned} E_{\mathrm{tot}}^{(n_p)} = \frac{K}{n_p}\left(320\times10^{-6}\right)\Bigg[&\frac{P_{\mathrm{i}}\,p_{\mathrm{CCA}}^{(n_p)}}{2}\left\{\frac{\left(1-x^{(n_p)}\right)\left(1-\left(2x^{(n_p)}\right)^{m+1}\right)}{\left(1-2x^{(n_p)}\right)\left(1-x^{(n_p)\,m+1}\right)}2^{macMinBE}-1\right\} \\ &+P_{\mathrm{s}}\,p_{\mathrm{CCA}}^{(n_p)}\left(2-\alpha^{(n_p)}\right)+\left(1-\alpha^{(n_p)}\right)\left(1-\beta^{(n_p)}\right)p_{\mathrm{CCA}}^{(n_p)}\left(\bar{n}_{\mathrm{succ}}^{\mathrm{UBP}}P_{\mathrm{t}}+P_{\mathrm{i}}+\left(P_{\mathrm{r}}\left(1-p_{\mathrm{c}}^{(n_p)}\right)+P_{\mathrm{i}}\,p_{\mathrm{c}}^{(n_p)}\right)\right)\Bigg]. \end{aligned} \tag{3-6}$$

It can be seen that the transmission failure rate and the energy consumption decrease as the partitioning number n_p increases. It can also be seen that the resource utilization ratio is a concave function of n_p. This is mainly due to the fact that unlike α and β, p_{CCA} decreases as the degree of contention for the packet transmission increases.

4. Proposed scheme

We consider the reduction of packet collision in IEEE 802.15.4 networks by adaptively partitioning the transmission period according to the network operation environment and existence of hidden node relationship between child devices. To this end, we consider recognition of network environment in contention collision alleviation algorithm and recognition of hidden node relationship in hidden node collision alleviation algorithm. After conducting recognition processes, the coordinator adaptively partitions the transmission period and each end device selects its own operation partition.

4.1. Proposed contention collision alleviation algorithm

4.1.1. Description of proposed scheme

We propose the hidden node collision alleviation scheme which reduces the hidden node collisions by recognizing hidden node relationship between child devices and making them activate in difference partitions. As depicted in fig 4.9, child devices which are in hidden node relationship operate in different partitions, avoiding hidden node collision. We consider three steps; recognition of hidden node collision, report of hidden node relationship and selection of the operating partition.

4.1.1.1. Recognition of operation environment

The network coordinator and child devices can measure the transmission performance in a distributed manner. IEEE 802.15.4 MAC sequentially allocates each packet a unique data sequence number (DSN). For ease of description, assume that the child device assigns zero DSN to the first packet and increases the DSN by 1 for the next packet. The network coordinator can estimate the transmission failure rate

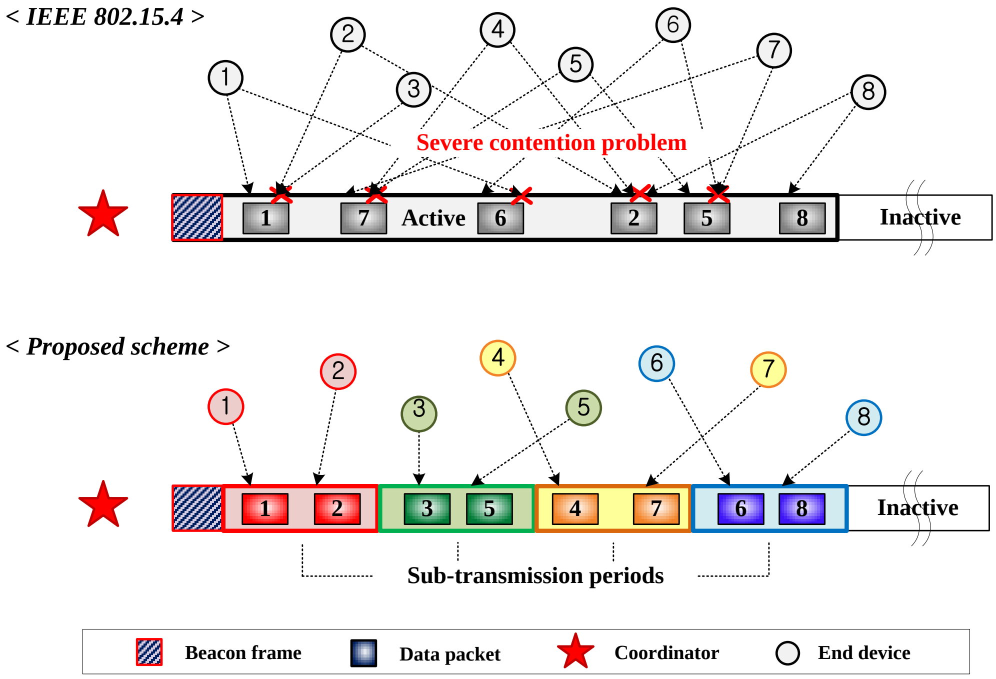

Fig. 4. 3. Concept of proposed contention collision alleviation scheme

$\tilde{R}_{\mathrm{f}}(t_i, t_j)$ between the end of the i-th super-frame and the end of the j-th super-frame (i.e., during time interval $[t_i, t_j]$) as

$$\tilde{R}_{\mathrm{f}}(t_i, t_j) = 1 - \frac{n_{\mathrm{succ}}(t_j) - n_{\mathrm{succ}}(t_i)}{\sum_{k=1}^{K} \left(d_k(t_j) - d_k(t_i) \right)} \tag{4-1}$$

where $d_k(t)$ denotes the DSN of the most recent packet successfully transmitted from child device k at time t and $n_{\mathrm{succ}}(t)$ denotes the total number of successfully transmitted packets at time t. It can also estimate the resource utilization ratio $\tilde{R}_{\mathrm{u}}(t_i, t_j)$ during time interval $[t_i, t_j]$ as

$$\tilde{R}_{\mathrm{u}}(t_i, t_j) = \frac{n_{\mathrm{succ}}^{\mathrm{UBP}}(t_j) - n_{\mathrm{succ}}^{\mathrm{UBP}}(t_i)}{\left(t_j - t_i \right) \times \left(aBaseSlotDuration / aUnitBackoffPeriod \right) \times 2^{SO}} \tag{4-2}$$

where $n_{\mathrm{succ}}^{\mathrm{UBP}}(t)$ denotes the total number of successfully transmitted packets in a unit of *aUnitBackoffPeriod* at time t.

Child node k estimates its transmission performance in terms of the transmission failure rate and the resource utilization ratio during time interval $[t_i, t_j]$ as, respectively,

$$\tilde{R}_{\mathrm{f}}^{k}(t_i, t_j) = 1 - \frac{n_{\mathrm{succ}}^{k}(t_j) - n_{\mathrm{succ}}^{k}(t_i)}{n_{\mathrm{total}}^{k}(t_j) - n_{\mathrm{total}}^{k}(t_i)} \tag{4-3}$$

$$\tilde{R}_{\mathrm{u}}^{k}(t_i, t_j) = \frac{n_{\mathrm{succ}}^{k,\mathrm{UBP}}(t_j) - n_{\mathrm{succ}}^{k,\mathrm{UBP}}(t_i)}{\left(t_j - t_i\right) \times \left(aBaseSlotDuration / aUnitBackoffPeriod\right) \times 2^{SO}} \tag{4-4}$$

where $n_{\mathrm{succ}}^{k}(t)$ is the number of packets successfully transmitted from child device k at time t, $n_{\mathrm{total}}^{k}(t)$ is the total number of packets transmitted from child device k at time t, and $n_{\mathrm{succ}}^{k,\mathrm{UBP}}(t)$ is the total number of packets successfully transmitted from child device k in a unit of *aUnitBackoffPeriod* at time t.

4.1.1.2. Centralized partitioning method

The network coordinator can solely determine the number of partitions by measuring the transmission performance. At the end of the i-th super-frame, it can measure the transmission failure rate $\tilde{R}_{\mathrm{f}}(t_{i-1}, t_i)$ and the resource utilization ratio $\tilde{R}_{\mathrm{u}}(t_{i-1}, t_i)$. Assume that the transmission failure rate should be higher than δ_{f} and the resource utilization ratio should be higher than δ_{u}. Let $n_{\mathrm{p},i}$ be the number of partitions used in the i-th super-frame. The larger the partitioning number of partitions, the lower the energy consumption. It may be desirable to maximally partition the transmission period, while providing desired transmission performance.

Fig. 4.2 summarizes the proposed centralized partitioning algorithm. If $\tilde{R}_{\mathrm{f}}(t_{i-1}, t_i) > \delta_{\mathrm{f}}$, the network coordinator increases the partitioning number by 1. Otherwise, the network coordinator calculates the tendency of resource utilization ratio, $I_{\mathrm{inc},i}$, as,

$$I_{\mathrm{inc},i}=\begin{cases}0, & \text{for } n_{\mathrm{p},i}=n_{\mathrm{p},i-1}\\ 1, & \text{for } n_{\mathrm{p},i}\neq n_{\mathrm{p},i-1} \text{ and } \left(n_{\mathrm{p},i}-n_{\mathrm{p},i-1}\right)\left(R_{\mathrm{u}}(t_{i-1},t_i)-R_{\mathrm{u}}(t_{i-2},t_{i-1})\right)>0\\ -1, & \text{for } n_{\mathrm{p},i}\neq n_{\mathrm{p},i-1} \text{ and } \left(n_{\mathrm{p},i}-n_{\mathrm{p},i-1}\right)\left(R_{\mathrm{u}}(t_{i-1},t_i)-R_{\mathrm{u}}(t_{i-2},t_{i-1})\right)\leq 0\end{cases}. \tag{4-5}$$

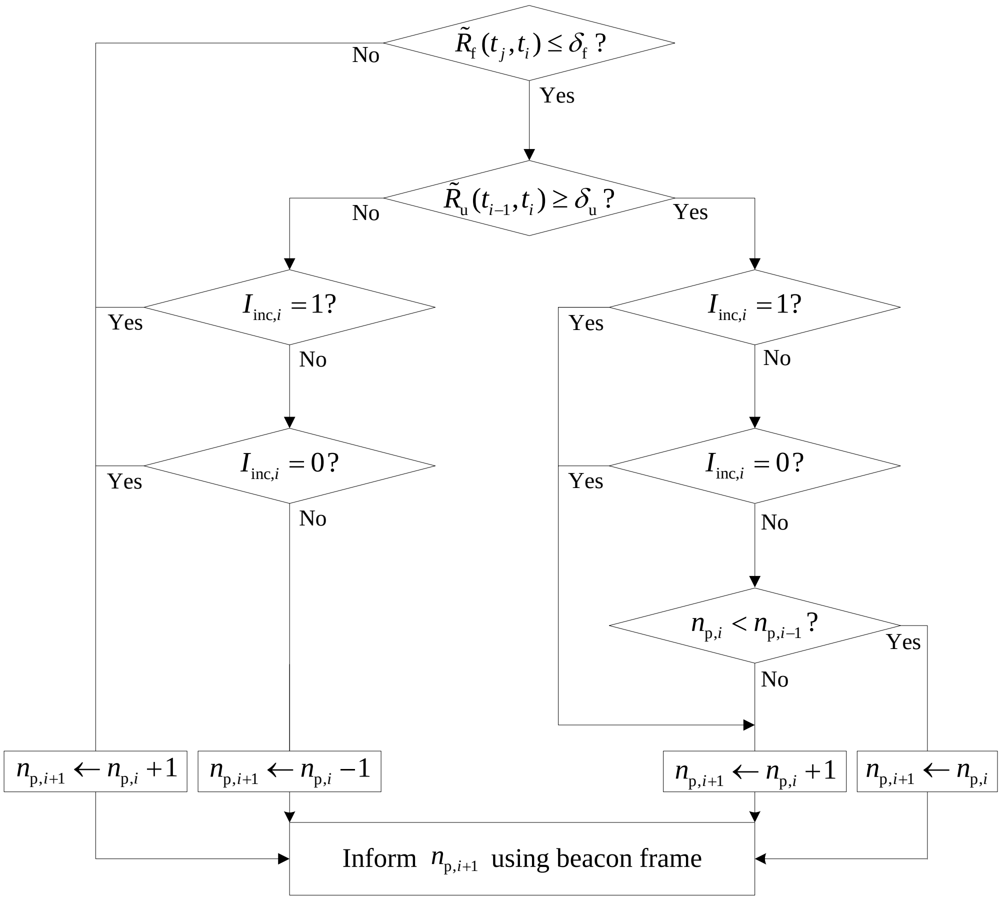

Fig. 4. 4. The proposed centralized partitioning process

$I_{\mathrm{inc},i}=1$ and $I_{\mathrm{inc},i}=-1$ imply that the resource utilization ratio is increasing and decreasing, respectively, and $I_{\mathrm{inc},i}=0$ denotes that $n_{\mathrm{p},i}$ is equal to $n_{\mathrm{p},i-1}$.

If $\tilde{R}_{\mathrm{u}}(t_{i-1},t_i)<\delta_{\mathrm{u}}$, the network coordinator increases the partitioning number by 1 when $I_{\mathrm{inc},i}=1$ and decreases it by 1 when $I_{\mathrm{inc},i}=-1$ to satisfy the resource utilization ratio requirement. If $\tilde{R}_{\mathrm{u}}(t_{i-1},t_i)\geq\delta_{\mathrm{u}}$ (i.e., the resource utilization ratio satisfies the requirement), the network coordinator may adjust the partitioning number to minimize energy consumption. If $I_{\mathrm{inc},i}=1$ or $I_{\mathrm{inc},i}=0$, it increases the partitioning number by 1. When $I_{\mathrm{inc},i}=-1$, the network coordinator keeps the partitioning number if $n_{\mathrm{p},i}<n_{\mathrm{p},i-1}$, and increases it by 1, otherwise. It notifies the updated partitioning number $n_{\mathrm{p},i+1}$ to its child devices using the beacon frame of the $(i+1)$-th super-frame.

4.1.1.3. Distributed partitioning method

The partitioning can also be performed in a distributed manner. The network coordinator can only determine whether the adjustment of the partitioning number is required or not. It sends a partitioning adjustment command to its child devices to request the change of the partitioning number. It generates the partitioning adjustment command $I_{\mathrm{part},i+1}$ at the $(i+1)$-th super-frame as

$$I_{\mathrm{part},i+1}=\begin{cases}0, & \text{for } R_{\mathrm{r}}(t_{i-1},t_i)\geq\delta_{\mathrm{r}} \text{ and } R_{\mathrm{u}}(t_{i-1},t_i)\geq\delta_{\mathrm{u}}\\ 1, & \text{otherwise}\end{cases} \tag{4-6}$$

where $I_{\mathrm{part},i+1}=1$ and 0 means that the need and no need of the change of the partitioning number at the $(i+1)$-th super-frame, respectively.

Fig. 4.3 summarizes the proposed partitioning at the $(i+1)$-th super-frame. Assume that the most recent partitioning process was done at the $(j+1)$-th super-frame. The child devices measure the total number of packets transmitted in time interval $[t_j,t_i]$ (i.e., $n_{\mathrm{total}}^k(t_i)-n_{\mathrm{total}}^k(t_j)$). When a sufficiently large number of packets have been transmitted (e.g., $n_{\mathrm{total}}^k(t_i)-n_{\mathrm{total}}^k(t_j)>\delta_{\mathrm{n}}$), where δ_{n} is a threshold level, the child

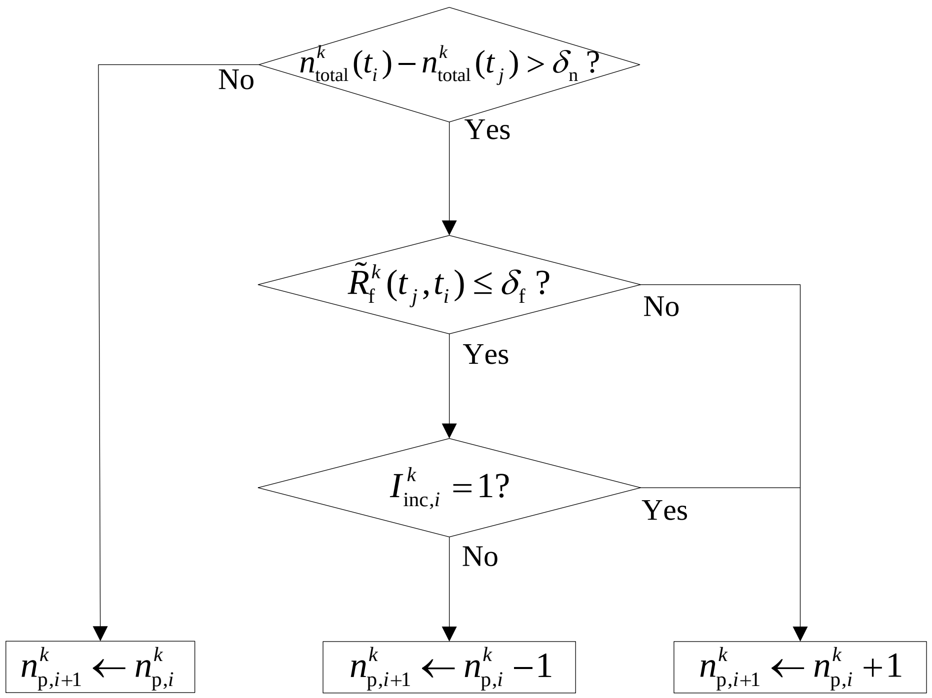

Fig. 4. 5. The proposed distributed partitioning process

device performs the partitioning process. Child device k measures its transmission failure rate $\tilde{R}_{\mathrm{f}}^{k}(t_j, t_i)$. If $\tilde{R}_{\mathrm{f}}^{k}(t_j, t_i) > \delta_{\mathrm{f}}$, it increases the partitioning number by 1. Otherwise, it estimates the tendency of its own resource utilization ratio, $I_{\mathrm{inc},i}^{k}$, as

$$I_{\mathrm{inc},i}^{k} = \begin{cases} 0; & \left(n_{\mathrm{p},i}^{k} - n_{\mathrm{p},j}^{k}\right)\left(\tilde{R}_{\mathrm{u}}^{k}(t_j, t_i) - \tilde{R}_{\mathrm{u}}^{k}(t_{\tilde{j}}, t_j)\right) > 0 \\ 1; & \text{otherwise} \end{cases} \tag{4-7}$$

where the most recent partitioning process before the j-th super-frame was done at the $\tilde{j}$-th super-frame. If the transmission failure rate condition is satisfied, the device increases the number of the partitions by 1 when $I_{\mathrm{inc},i}^{k} = 1$ and decreases it by 1 when $I_{\mathrm{inc},i}^{k} = -1$ to increase the resource utilization ratio. Finally, it partitions the transmission period into $n_{\mathrm{p},i+1}^{k}$ partitions.

4.1.1.4. Selection of the portioned partition

Each child device can determine a partition for its packet transmission without control from the network coordinator. For example, it can determine its partition by using the network address and the partitioning number. For a determined value of $n_{\mathrm{p},i+1}^{k}$, child device k can determine its partition P_{i+1}^{k} at the $(i+1)$-th super-frame as

$$P_{i+1}^{k} = 1 + \mathrm{mod}\left(n_{\mathrm{p},i+1}^{k}, A^{k}\right) \tag{4-8}$$

where A^k is the network address of child device k and " $\mathrm{mod}(\bullet, \bullet)$ " denotes the modulo operation. As in fig. 4.4, with this partitioning process, it stays in the idle state during $\left[0, T_{\mathrm{part},i+1}^{k}\left(P_{i+1}^{k} - 1\right)\right]$, transmits packets in a contention manner during $\left(T_{\mathrm{part},i+1}^{k}\left(P_{i+1}^{k} - 1\right), T_{\mathrm{part},i+1}^{k} P_{i+1}^{k}\right]$ and again stays in the idle state during $\left(T_{\mathrm{part},i+1}^{k} P_{i+1}^{k}, t_{\mathrm{BI}}\right)$, where the length of each partition can be represented as

$$T_{\mathrm{part},i+1}^{k} = \frac{t_{\mathrm{SD}}}{n_{\mathrm{p},i+1}^{k}}. \tag{4-9}$$

4.1.2. Simulation results

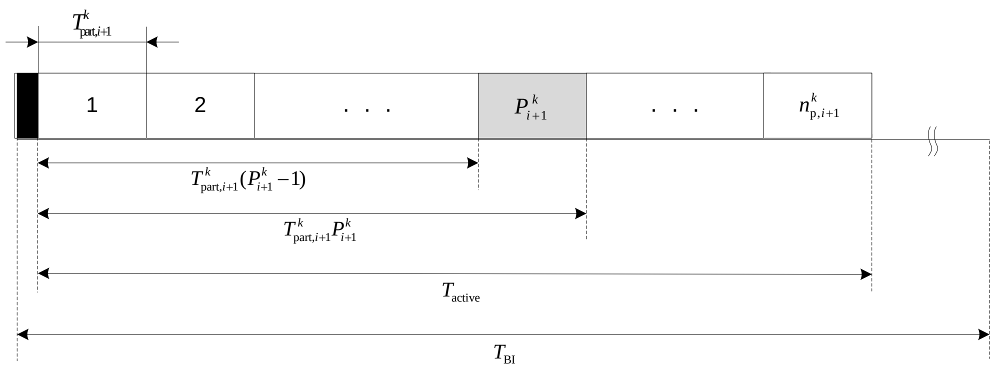

Fig. 4. 6. Operation of device k in $(\mathbf{i+1})$-th super-frame

The performance of the two proposed schemes has been verified by computer simulation. The simulation environment is summarized in Table I, which considers the operation of an IEEE 802.15.4 based network with a star-topology structure in the beacon-enabled mode with the use of slotted CSMA/CA. For comparison, the performance of conventional CSMA/CA of IEEE 802.15.4, ECR and ECAM has also been evaluated.

Table. 4. 1. Simulation parameter

Parameters	Values
Beacon order (BO)	4
Super-frame order (SO)	3
Packet size	40 bytes
Total offered load	70 kbps
Power consumption in active reception (P_{rx}) [11]	78.3 mW
Power consumption in packet transmission (P_{tx}) [11]	70.0 mW
Power consumption in CCA (P_{CCA}) [11]	83.0 mW
Power consumption in idle mode (P_{idle}) [11]	3.79 mW
Transmission failure rate requirement (δ_{f})	0.1
Resource utilization ratio requirement (δ_{u})	0.5

Fig. 4.5 depicts the transmission failure rate of the three schemes according to the number of child devices when the total offered load of the network is fixed to 70 Kbps (e.g., operation of 20 child devices transmitting at a rate of 3.5 Kbps). It can be seen that as the number of device increases, the transmission failure rate of the conventional schemes increases, which is mainly due to the increase of contention

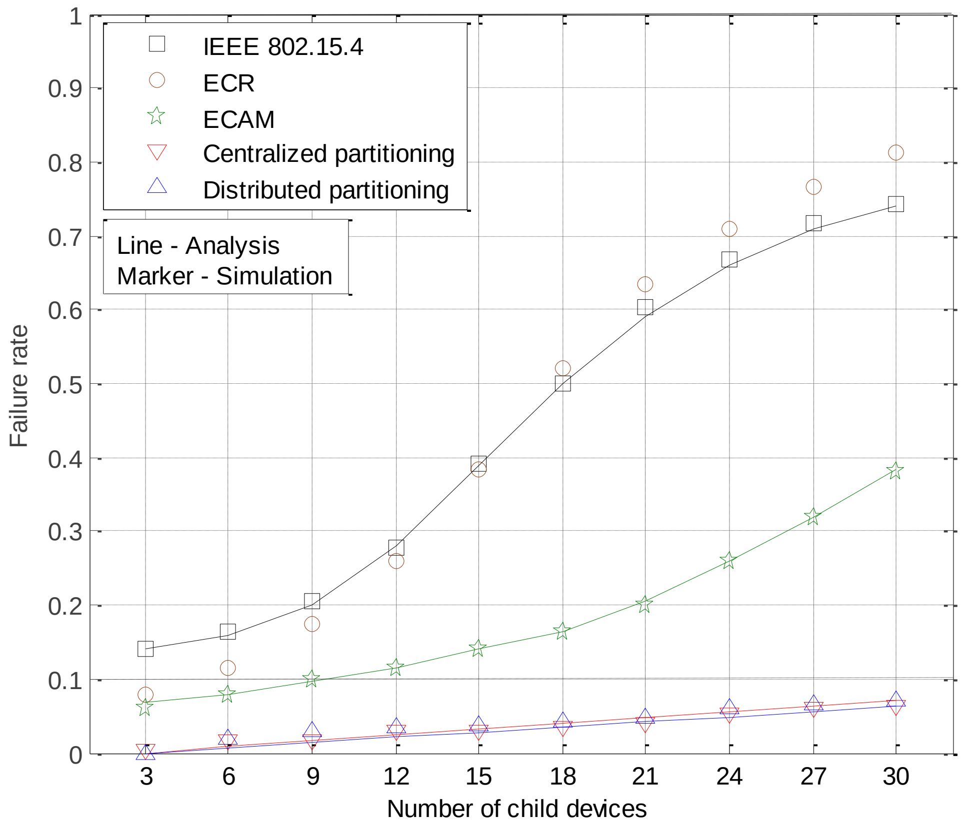

Fig. 4. 7. Failure rate according to the number of devices

collision. The ECAM also suffers from severe contention collision in high-traffic environments. As a consequence, it exceeds the desired transmission failure rate 0.1 if the number of child devices is larger than 9. It can be seen that the two proposed partitioning schemes can provide desired transmission failure rate.

Fig. 4.6 depicts the average number of partitions used by the two proposed schemes

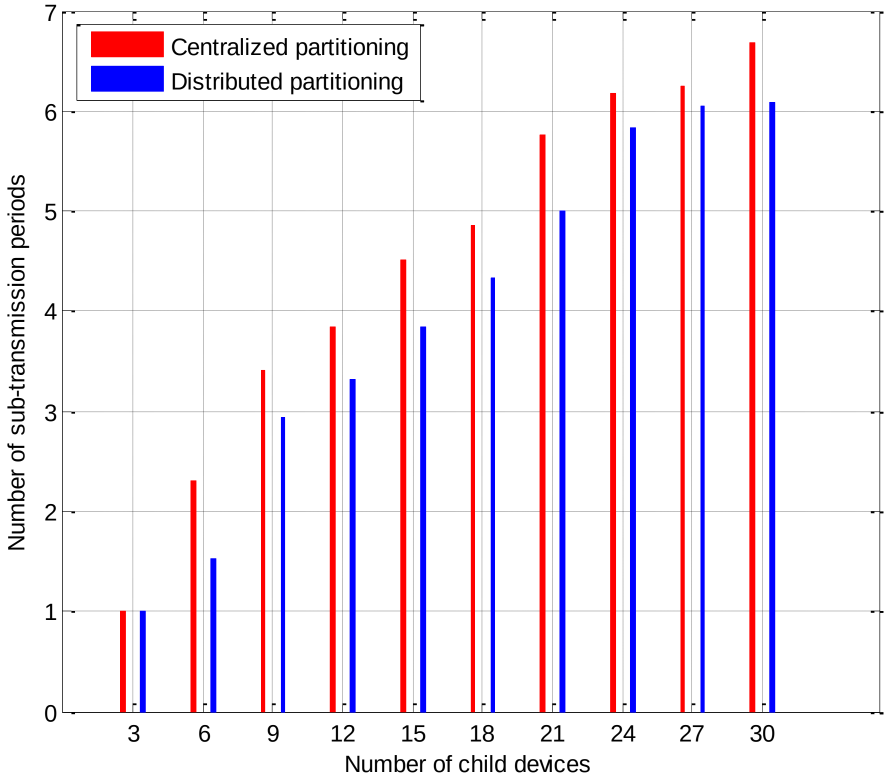

Fig. 4. 8. Average number of partitions used by the two proposed schemes

under the same condition as in Fig. 4.5. It can be seen that the two schemes use different partitioned partitions. This is mainly due to the fact that the centralized scheme is mainly aimed to minimize energy consumption, while the distributed scheme is mainly aimed to maximize resource utilization.

Fig. 4.7 depicts the total transmission throughput and energy consumption of the

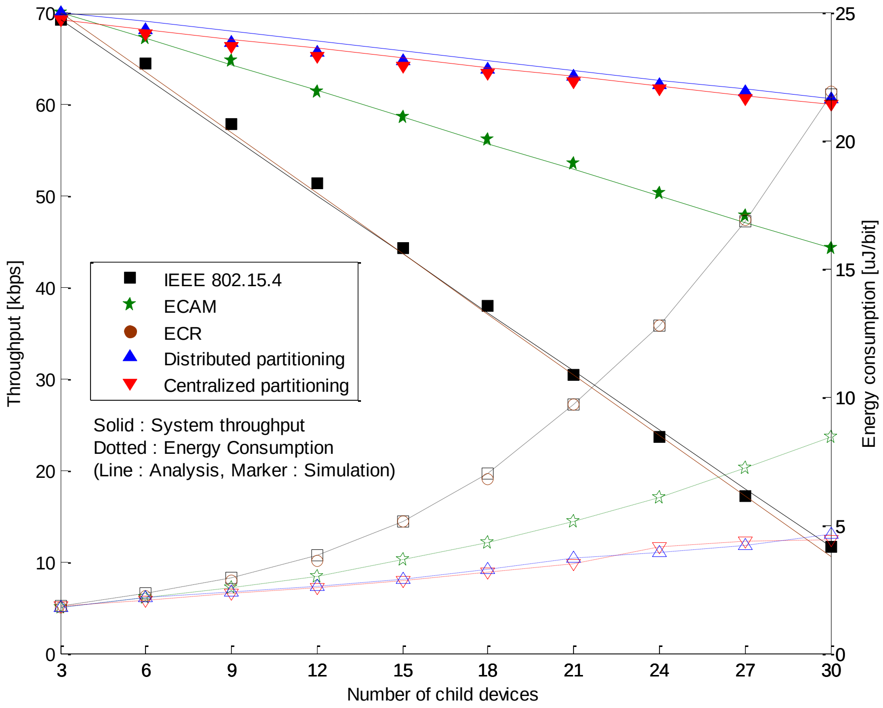

Fig. 4. 9. System throughput and energy consumption according to the number of devices

network. It can be seen that the total throughput of IEEE 802.15.4 and ECR significantly degrades as the number of child devices increases. This is mainly due to the fact that the packet collision increases as the number of devices increases. The proposed schemes somewhat reduce the packet collision by increasing the partition as the number of child devices increases, providing transmission throughput slightly lower than the total offered load. It can also be seen that the distributed partitioning scheme provides slightly higher transmission throughput than the centralized one since it is designed to maximize resource utilization. It can also be seen that the proposed schemes significantly reduce energy consumption as the number of child devices increases. Since the amount of the total offered load is fixed to 70 Kbps, the transmission rate of each child device decreases as the number of child devices increases. Each IEEE 802.15.4 device uses the whole transmission period regardless of the data rate, yielding the increase of energy consumption as the number of devices increases. On the other hand, the proposed schemes allow the devices to use a partitioned sub-period, increasing the inactive period (i.e., saving energy consumption). Moreover, they provide low transmission failure rate, further reducing energy consumption.

Fig. 4.8 depicts the transmission failure rate when 5 child devices are additionally activated every 200 beacons interval. We assume that each child device transmits packets at a data rate of 2.33 kbps. It can be seen that as the number of activated child devices increases, IEEE 802.15.4 suffers from severe contention collision, yielding high transmission failure rate. On the other hand, the proposed schemes can maintain desired transmission failure rate by adjusting the partition according to the presence of additional activated child nodes, which may take a time to measure the measured transmission performance. It can also be seen that the distributed partitioning scheme shows slower adaptation than the centralized one, mainly because it can start the partitioning process after the transmission of at least δ_n packets.

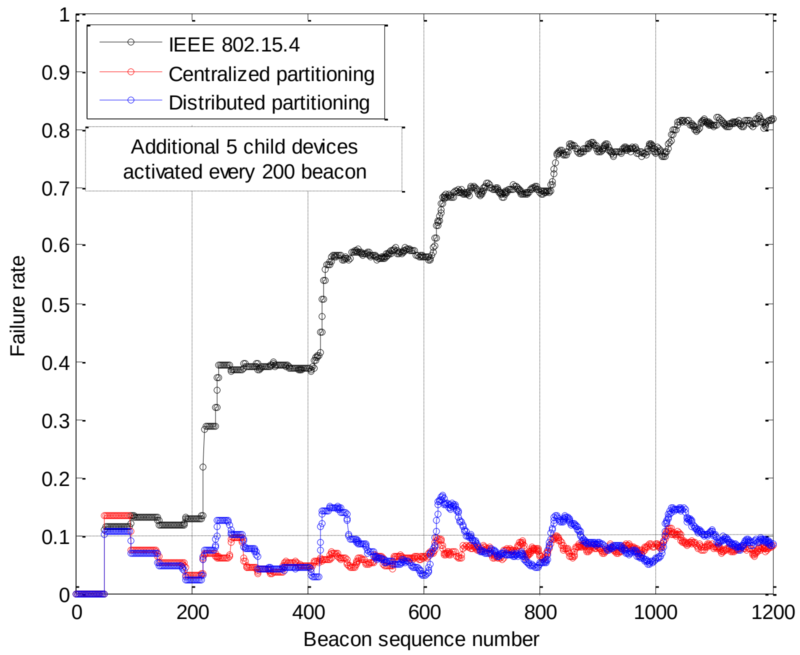

Fig. 4. 10. Transmission failure rate associated with the increase of activated child devices

4.2. Proposed hidden node collision alleviation scheme

4.2.1. Description of proposed scheme

We propose the hidden node collision alleviation scheme which reduces the hidden node collisions by recognizing hidden node relationship between child devices and making them activate in difference partitions. As depicted in fig 4.9, child devices which are in hidden node relationship operate in different partitions, avoiding hidden node collision. We consider three steps; recognition of hidden node collision, report

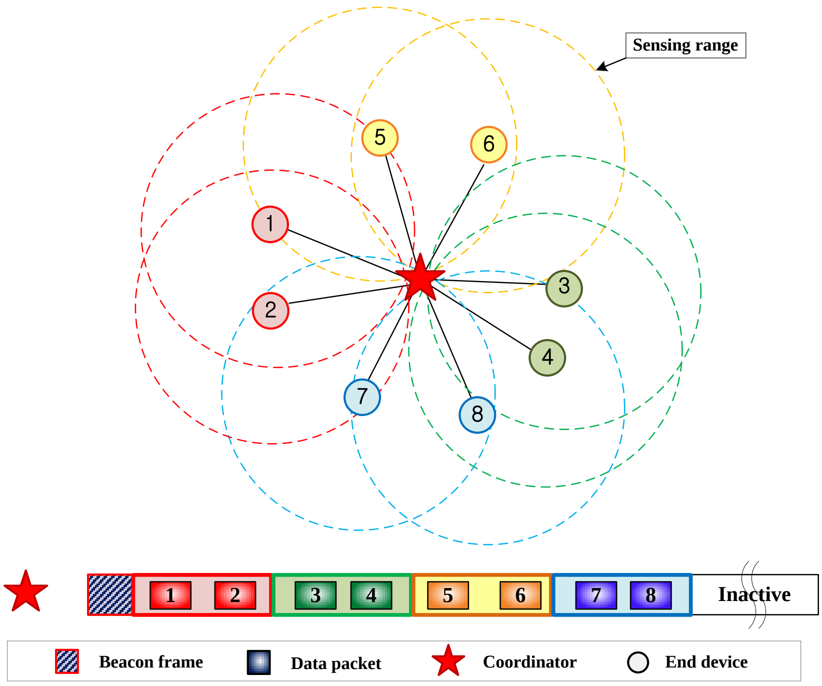

Fig. 4. 11. Concept of proposed hidden node collision alleviation scheme

of hidden node relationship and selection of the operating partition.

4.2.1.1. Recognition of hidden node collision

In CSMA/CA-based networks, the contention collision occurs only when multiple child devices choose the same time to transmit data packets. In this case, transmitted signals will be collided from the beginning of the packet transmission. However, the hidden node collisions occurs when two nodes unhearing to the other send data packets simultaneously. If synchronization between child devices is perfectly achieved with periodic beaconing, contention collision and hidden node collision can be distinguished precisely because hidden node packet collision does not damage the preamble of first transmitted data packet[7]. However, FCS of the packet(in fig. 4.10) is corrupted when packet collision occurred. Therefore, the coordinator may recognize the hidden node collision when the preamble is decodable while the FCS is corrupted. After recognizing the hidden node collision, the coordinator fisrt checks whether the hidden node collision is occurred due to the interference signal or not. In the following inactive period, the coordinator performs energy detection-based channel sensing to verify the existence of interference signals. The coordinator performs interference management schemes under hypothesis H_1, or advance to next step to alleviate hidden node collision.

4.2.1.2. Report of hidden node relationship

To detect hidden node relationships between child devices, we employ a pending mechanism in IEEE 802.15.4 standard to reduce additional message transactions. The coordinator broadcasts beacon with pending notification which targets to the device whose address is recognized in step 1. The coordinator set *HNP_alleviation_field* in beacon as 1 to inform that the following pending process is not for indirect packet transmission but for hidden node alleviation. After receiving beacon signal, targeted device transmits data request message as acknowledgement of pending notification. Hidden devices(child devices that are in hidden node relationship with the targeted device) can receive beacon frame but data request message. After receiving data request message, the coordinator set hidden node reporting period(e.g., n_{rep} super-frames) and hidden devices report hidden problem to the coordinator during reporting period. Threre are two ways to report the hidden problem; create reporting packet and

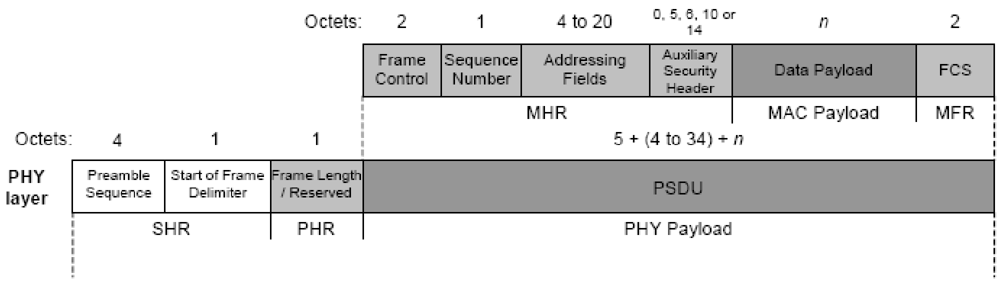

Fig. 4. 12. The structure of data packet frames

transmit it with CSMA/CA method or piggyback hidden problem report in a normal data packet.

4.2.1.3. Selection of operating partition

When the hidden problem is reported, the coordinator transmits acknowledgement frame to the source device. Contrast to contention collision alleviation scheme, child devices do not choose their operating partition with their own network address. Assuming that child device k operates in P_i^k-th partition at the i-th super-frame. After receiving the acknowledgement frame from the coordinator, the child device k determines its own operating partition P_{i+1}^k-th at the $(i+1)$-th super-frame as,

$$P_{i+1}^k = \mathrm{mod}(P_i^k + 1, n_{\mathrm{p},i+1}^k) \tag{4-5}$$

where $\mathrm{mod}(\bullet, \bullet)$ denotes the modulo operation and $n_{\mathrm{p},i+1}^k$ denotes the number of partitions in $(i+1)$-th super-frame, which can be determined as,

$$n_{\mathrm{p},i+1}^k = \max\left\{P_{i+1}^k\right\},\ k = 1,\cdots,K. \tag{4-6}$$

In this way, child devices that are in hidden node relationship can avoid hidden node collision.

4.2.2. Simulation results

The performance of the two proposed schemes has been verified by computer simulation. The simulation environment is summarized in Table II, which considers the same operation environment, the operation of an IEEE 802.15.4 based network with a star-topology structure in the beacon-enabled mode with the use of slotted CSMA/CA. We assume that no interference signal is exist.

Table. 4. 2. Simulation parameter

Parameters	Values
Beacon order (*BO*)	4
Super-frame order (*SO*)	3
Transmission range	20 m
Sensing range	20 m
Packet size	40 bytes
Offered load per each device	2 kbps
Maximum number of partitions	4

Figure 4.11 depicts the packet collision ratio according to the number of child devices when the offered load of each device is 2 kbps. It can be seen that as number of device increases, successful transmission ratio decreases, which is mainly due to the increase of packet collisions. Because maximum number of partitions is fixed to 4,

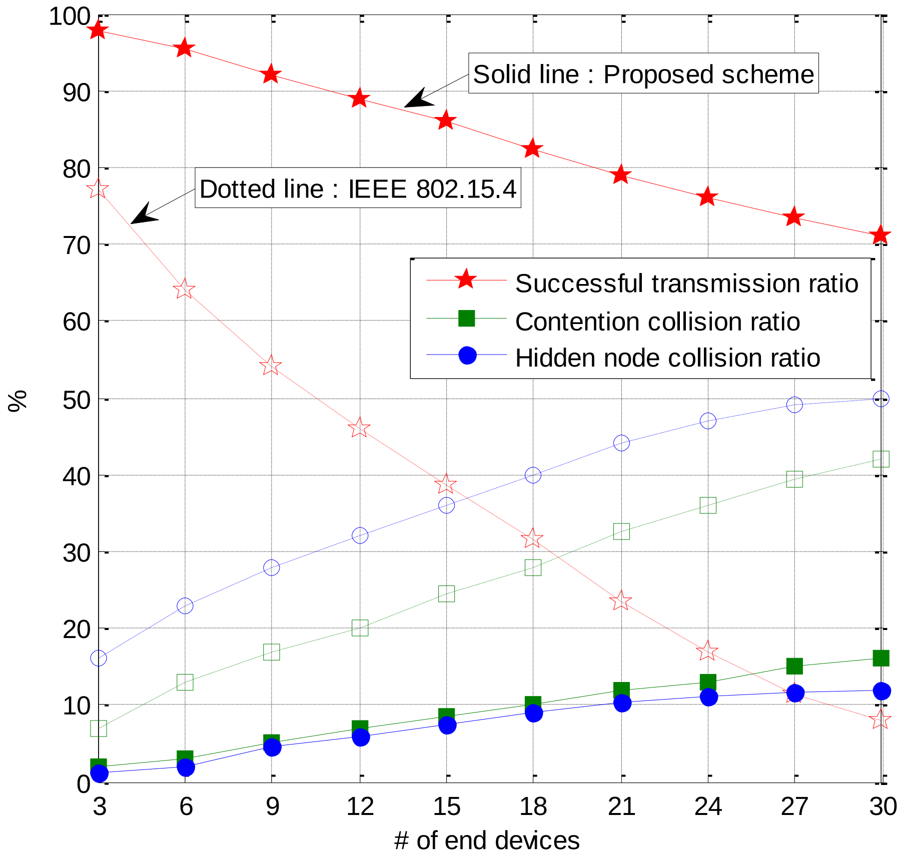

Fig. 4. 13. Packet collision ratio according to the number of child devices

hidden node collisions are still occurred in each partition. Proposed scheme divides active period into multiple partitions, also alleviating contention collisions. However, constrast to contention collision alleviation scheme, it may not guarantee transmission failure rate lower than specific threshold(e.g. 10%). This is mainly due to the fact that hidden node alleviation scheme does not adaptively change the number of partitions but divides active period into fixed number of partitions. Even when the number of child devices is 30, proposed scheme guarantees successful transmission more than 70%.

Fig. 4.12 depicts the aggregate throughput according to the number of child devices under the same condition as in fig.4.11. Proposed scheme shows high throughput performance close to total offered load. This is mainly due to the high successful transmission ratio described in fig 4.11. As the number of child devices increases, proposed scheme also shows larger gap with the total offered load, because of the increase of contention in each partition. In this reason, every protocol using CSMA/CA shows lower performance as the number of contending devices increases.

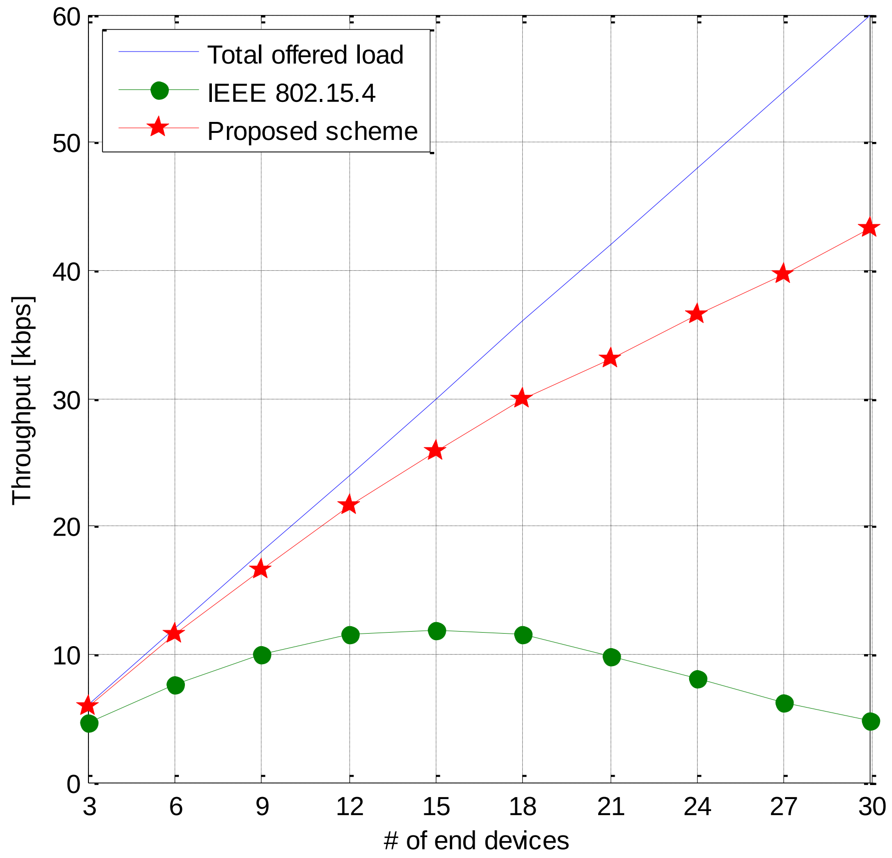

Fig. 4. 14. Aggregate throughput according to the number of child devices

5. Conclusions

In this thesis, we have considered the alleviation of packet collision in IEEE 802.15.4-based networks. To this end, a network coordinator first measures the network transmission performance using statistics of transacting data packets and recognizes hidden node relationships between child devices by using the pending mechanism in IEEE 802.15.4. When the measured performance is not satisfactory, the coordinator adjusts the number of partitions according to the operation environment to alleviate contention collisions. Furthermore, the child devices that are in hidden node relationship automatically choose different transmission periods to avoid hidden node collision. The proposed partitioning scheme can remarkably reduce the failure rate and energy consumption, while efficiently alleviating packet collisions. Finally, the effectiveness of the proposed scheme has been evaluated by computer simulation in time-varying operation environments.

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초 록

최근, 저전력 저복잡도를 특징으로 하는 IEEE 802.15.4 표준은 배터리(battery)를 기반으로 동작하는 센서 네트워크에 가장 적합한 매체 접근 제어(medium access control: MAC) 규약으로 떠오르고 있다. 단말기기는 주통신기기(coordinator: 이하 코디네이터)에 저전력으로 패킷을 전송하기 위하여 저전력 CSMA/CA(carrier sense multiple access with collision avoidance)를 사용하며, 적은 메시지 부담(overhead)으로 높은 성능을 나타낸다. 하지만, 다수의 패킷이 전송되는 환경에서 저전력 CSMA/CA 는 패킷 간의 충돌에 의해 성능이 크게 저하되는 문제가 발생한다. 본 논문은 다수의 단말기기들이 저전력 CSMA/CA 기반의 경쟁적 방식을 사용하여 코디네이터에게 신호를 전송하는 무선 통신 시스템에서 단말기기 간의 패킷 충돌 문제를 완화시켜 통신 성능을 향상시키는 방법에 관한 것이다.

저전력 CSMA/CA 는 동시에 채널이 유휴(idle)함을 인지한 다수의 단말기기가 동시에 신호를 전송함으로써 발생하는 경쟁 충돌(contention collision)과 다른 단말기기의 신호 전송을 인지하지 못한 단말기기가 채널이 유휴하다고 판단하고 신호를 전송함으로써 발생하는 히든 노드 충돌(hidden node collision)에 의해 심각한 전송 성능 저하가 발생한다. 본 논문에

서 제안하는 기법은 현재 네트워크 전송 성능과 히든 노드(hidden node) 관계의 존재 여부를 적은 메시지 교환 오버헤드를 이용해 인지하고, 이에 따라 전송 가능 구간을 여러 개의 소구간으로 분할하여 각 단말기기가 스스로 정한 소구간 기간 동안에서만 전송을 시도하게 함으로써 단말기간의 전송 경쟁에서 발생하는 전송 충돌 문제를 효율적으로 완화시킬 수 있다. 더불어, 다른 단말기기와 히든 노드 관계가 있음을 인지한 단말기기는 자신이 동작할 소구간을 결정하는 과정에서 히든 노드 관계에 있는 단말기기는 서로 다른 소구간에서 동작하게 함으로써 히든 노드 관계에 의해 발생한 신호 충돌 문제를 효과적으로 줄인다. 이를 통해 본 논문에서 제안하는 기법은 경쟁 기반의 전송 프로토콜 하에서 패킷 충돌을 완화하여 시스템에서 요구하는 전송 성능을 만족함과 동시에 전력 효율을 높일 수 있다.

主要語: IEEE 802.15.4, CSMA/CA, 패킷 충돌, 전송 구간 분할

학번 : 2011-20822