Intra-Superframe Power Management for IEEE 802.15.3 WPAN

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***Abstract*— Power management (PM) is critical for the portable devices in IEEE 802.15.3 Wireless Personal Area Networks (WPAN). Due to the property of TDMA based MAC of 802.15.3, one of the key issues for PM is to schedule the order of the multiple streams among multiple users to minimize the total wakeup times. In this paper, we reveal that this PM problem is in general a Hamilton path problem. With the aid of graph theory, we derive the lower bound and upper bound for the minimum wakeup times. Then, an efficient MDS (Min-Degree Searching) algorithm is proposed to find the suboptimal order. The simulation results show that the MDS algorithm is usually near-optimal and can actually achieve the lower bound in most cases and performs much better than existing approach.**

***Index Terms*— Power management, IEEE 802.15.3, superframe.**

I. Introduction

IEEE 802.15.3 has gained much research attention recently and it is to enable a high-speed and low-power wireless connectivity among portable devices within a WPAN [1]. In particular, it will act as a MAC support for Ultra-Wideband (UWB). IEEE 802.15.3 MAC is mainly based on Time Division Multiple Access (TDMA) and it defines a wireless ad hoc network (piconet) allowing a number of devices (DEV) to communicate with each other in a peer-to-peer mode. One of the DEVs is selected as piconet coordinator (PNC) to perform the central controlling functions, e.g., system timing, QoS, power management, etc.

PM is an important issue for the battery-powered portable devices and its objective is to assist the devices to sleep and reduce the wakeup as much as possible. There has been several work in literature on the MAC design for PM in wireless systems. But most of them were based on the MAC of 802.11 WLAN [2]–[4] and no work report on IEEE 802.15.3 systems so far. In particular, in [4], some directory protocols are proposed and they can be used by a central node in a wireless network such as 802.11 PCF (Point Coordination Function) mode to coordinate the data transmission and the sleeping. A transmission scheduling algorithm is proposed to arrange the order of the streams to save power. Since the algorithm is designed for 802.11 PCF, it can be well applied to 802.15.3.

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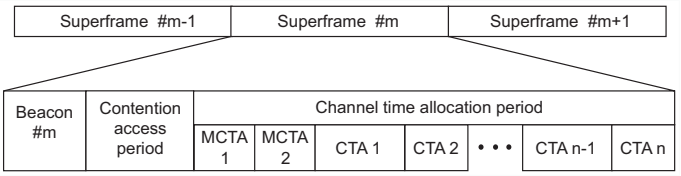

Fig. 1. Superframe structure of IEEE 802.15.3.

In this paper, we consider the PM for the TDMA based 802.15.3 WPAN. In 802.15.3 standard, several power saving modes such as Device Synchronized Power Save (DSPS) have been defined. These modes enable DEVs to sleep for one or more superframes (SFs, SF will be described next) to save power. We call this as inter-SF PM. On the other hand, we will show that when a DEV has multiple streams, the relative positioning of the streams from all DEVs within a TDMA SF affects the total number of wakeup and thus has a significant effect on the power. We call this as intra-SF PM problem. In this paper, we abstract this to be a Hamilton path problem. Under some special cases, Euler path can be used to retrieve the optimal solution. Then, we propose an efficient sub-optimal MDS algorithm. Simulations demonstrate that it can achieve the optimal solution with a probability of more than 95% and outperform the existing approach in [4] significantly.

II. Intra-Superframe PM in IEEE 802.15.3

In 802.15.3, time is divided into multiple SF and a typical SF structure is shown in Fig. 1. Since the CSMA-based Contention Access Period is optional in standard [1], we do not consider it here. Only the TDMA-based Channel Time Allocation Period is considered where multiple streams share different time slots named Channel Time Allocations (CTAs). The PNC assigns a CTA for each stream and announces the position and the duration of the CTA in the beacon at the beginning of SF. The standard does not define how to assign the CTAs and leaves this for vendors. In this paper, we assume that the duration of the CTA for each stream has been calculated, which is a classical QoS scheduling problem. Then, the next problem is how to assign the positions of these CTAs within the SF to save power as shown below.

Due to the property of TDMA MAC, each DEV can know exactly the CTA position in the SF from the beacon. Thus, the DEV can go to sleep during the CTAs not assigned for its

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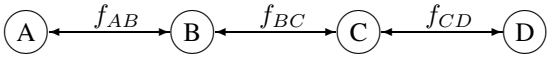
streams and only wake up during the CTAs for its streams [1]. As a result, when a DEV has multiple streams, it may wake up and sleep for several times if the CTAs/streams are not well ordered. On the other hand, each wakeup and sleeping will consume much power [6]. So, the intra-SF PM turns out to be properly arranging the order of the DEVs' streams to minimize the total number of wakeups in a typical multi-user and multi-stream network. A sample topology below shows the effect of the stream ordering on PM. Here, DEV B has a stream between DEV A and DEV C; and DEV D has a stream between DEV C.



For this topology, we have two possible stream orders:

- Order 1: $f_{AB} \rightarrow f_{BC} \rightarrow f_{CD}$, wakeup times=4
- Order 2: $f_{AB} \rightarrow f_{CD} \rightarrow f_{BC}$, wakeup times=5

For order 1, every two contiguous streams share a common DEV. Since each DEV wakes up only in its own CTA and then go to sleep at the end of the CTA, the total number of wakeups is four. (Note that the first stream f_{AB} requires two DEVs to wake up.) For order 2, however, DEV B will go to sleep state after stream f_{AB}, and then need to wake up again in the third CTA for stream f_{BC}. So, the total number of wakeups is five, which is worse than order 1.

III. Proposed Approach

We consider a multiple-DEV, multiple-stream 802.15.3 WPAN. Note that if there is more than one stream between two DEVs, we can combine them as a single stream since it is natural to put them at contiguous CTAs within the SF. Thus, we can generate a graph with the following rules:

1. Each DEV is denoted as a vertex.
2. Add an edge between two vertexes if there is a stream between the two corresponding DEVs.

The graph generated as above is called G1 in this paper. An example of G1 is shown on the left side of the Fig. 2 (the right side G2 will be explained next). Now, assume there are M vertexes and N edges in G1. The PM problem is translated to *finding an order of the edges in G1 so that every two contiguous edges share a common vertex*. Since each time we serve a new stream, at least one new DEV needs to wake up, then, we have the following lemma which is straightforward to prove.

Lemma 1: **The minimum number of the wakeups is lower bounded by $N + D$ with D denoting the number of connected patches in graph G1.**

According to Lemma 1, when G1 is a connected graph, the lower bound of the minimum number of the wakeups is $N + 1$. Obviously, if an Euler Path [5] exists in G1, then the edge order in this path is the optimal solution to achieve the lower bound. An example is shown in G1 of Fig. 2 where an Euler Path is found to be: $e_1 \rightarrow e_2 \rightarrow e_3 \rightarrow e_4 \rightarrow e_5 \rightarrow e_6$. However, we will point out later that Euler Path is a sufficient but not necessary condition for our PM problem here. Nevertheless, based on the property of Euler Path, we have the following lemma.

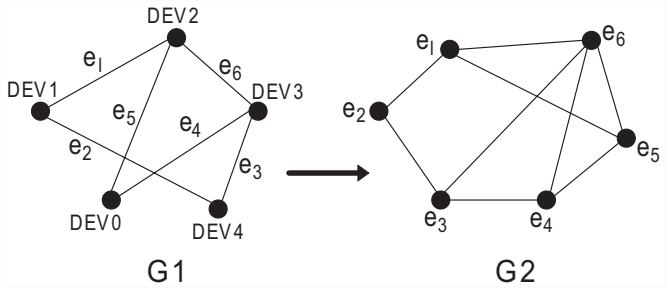


Fig. 2. Transformation of G1 to G2.

Lemma 2: **Assume the number of odd vertexes (odd vertex denotes the vertex with odd degree) is L in a connected graph G1. If $L \leq 2$, the minimum number of wakeups for the PM is equal to $N + 1$, which achieves the lower bound; If $L > 2$, the minimum number of wakeups for the PM is upper bounded by $N + L/2$.**

Proof: Note that L is always even in a graph. It is well known that when $L \leq 2$, the Euler Path (not necessary an Euler circuit) exists in G1 [5]. Then, the Euler Path yields the optimal solution and thus, the minimum number of wakeups is $N + 1$. When $L > 2$, we can add $(L - 2)/2$ edges between the $L - 2$ odd vertexes. Then, the Euler Path exists in this modified graph. Next, by removing the $(L - 2)/2$ edges from the Euler Path, we can immediately see that it is a solution with wakeup times being $N + 1 + (L - 2)/2 = N + L/2$. But note that this may not be the optimal solution. ■

It is known that the Euler Path can be found by Fleury Algorithm [5]. Although at the first glance, the Euler Path seems equivalent to the PM problem we defined here, it is actually a sufficient but not necessary condition. This is because, in the edges' order obtained from Euler Path, the ending vertex of an edge should be the initial vertex of the successive edge. However, for the PM problem we defined in G1, two contiguous edges in the optimal order can share the common initial vertex. For example, in G1 of Fig. 2, the edge order $e_1 \rightarrow e_6 \rightarrow e_5 \rightarrow e_4 \rightarrow e_3 \rightarrow e_2$ is also an optimal order although it is not even a path at all. Therefore, the existence of Euler Path is too strong a condition for our PM problem. In other words, it is sufficient but not necessary. To gain further insight on this problem, we can transform G1 to another equivalent graph G2 by obeying the following rules:

1. Each edge in G1 is denoted as a vertex in G2.
2. Add an edge between two vertexes in G2 if the corresponding two edges in G1 are neighbors.

From G2, we can immediately see that the optimal stream order is equivalent to finding a path in G2 so that G2 can be vertex-traversed; and this path is actually the Hamilton Path. Unfortunately, so far, in academia, unlike the Euler Path, there is no useful method to determine the existence of the Hamilton Path, let alone how to find it [5]. Therefore, in the following, we propose a MDS algorithm to find the suboptimal order of the streams.

Our goal is to find an order of the streams so that the contiguous streams can always share a common DEV. Of course, this is not always achievable. Anyway, for a given graph, there must exist an optimal order although it may not

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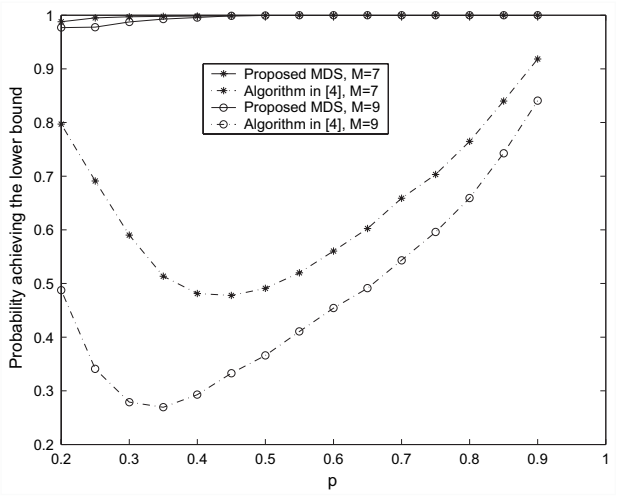

Fig. 3. Comparison between MDS and existing algorithm.

achieve the lower bound. The exhaustive search of the optimal order has a complexity of $N!$, which is unaffordable. Thus, we propose an MDS algorithm. The basic idea of our proposed MDS algorithm is that, each time we select an edge in G1 so that its two associated vertexes have the minimum degree. Its motivation is that the edges with associated small degree of vertexes are the ones most likely to be isolated. So, we serve them first when it is still possible for them to share common vertex with other edges. The details of MDS are described as follows:

1. Let $G = G1$; $j = 0$.
2. Select an edge as e_j in G so that both two associated vertexes are with the minimum degree. (Here, both two vertexes having the minimum degree means that first, among all candidate vertexes, find those with the minimum degree (> 0). Then, for each of them, among its neighboring vertexes, find one with the minimum degree. Finally, choose the vertexes pair with the minimum degree.)
3. For the current set $\{e_0, e_1, \cdots, e_j\}$, in $G = G1 - \{e_0, e_1, \cdots, e_{j-1}\}$, if the neighboring edges of $e_j = \emptyset$, go to step 5; otherwise, among the neighboring edges of e_j, select an edge as e_{j+1} so that both two associated vertexes are with the minimum degree; $j = j + 1$.
4. Continue step 3 until it cannot proceed.
5. If $E - \{e_0, e_1, \cdots, e_j\} \neq \emptyset$, let $G = G1 - \{e_0, e_1, \cdots, e_j\}$ and go back to Step 2; otherwise, stop.

IV. Simulation Results

In this section, to evaluate our MDS, the algorithm in [4] is selected for comparison where the edges belonging to the same DEV are first grouped in a descending order of the vertex degree. That is, first select the vertex with the maximum degree and group all its edges. Then, in the remaining vertexes and edges, select the vertex with the maximum degree, and so on. Obviously, the edges in the same group always share a common vertex. The algorithm then does some optimizations trying to connect different groups.

In our simulation, we assume that there is a stream between each pair of the M DEVs with probability p. Obviously, the larger p is, the more edges will be in G1. Here, we mainly evaluate the probability that the algorithm achieves the lower bound for the minimum wakeup times described in Lemma 1. In Fig. 3, we compare MDS with the algorithm in [4] under $M = 7$ and $M = 9$ DEVs. Totally, 10000 topologies are simulated for each p. We can see that MDS far outperforms the algorithm in [4] and it can achieve the lower bound in more than 95% cases. This also indicates that MDS can achieve the optimal solution in most cases.

V. Conclusions

In this paper, an intra-SF PM problem is studied in an IEEE 802.15.3 system. The major issue for this problem is to schedule the order of streams so that the total wakeup times can be minimized. With the aid of the graph theory, we translated the problem to a Hamilton Path problem and derived the lower bound and the upper bound for the minimum wakeup times. We then proposed an MDS algorithm and the simulations showed that it far outperforms the existing algorithm and achieves the lower bound in most cases.

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