Asynchronous multi-channel neighbour discovery for energy optimisation in wireless sensor networks

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Abstract: Neighbour discovery is a process that new devices gather the information from their neighbours when they initially join in a wireless sensor network. During this process, energy utilisation efficiency serves as an essential evaluated factor to concern. This paper proposes a novel asynchronous multi-channel neighbour discovery method for the energy-sensitive time division multiple access (TDMA) wireless sensor network. Two aspects are designed to enhance the efficiency of the energy utilisation, including minimising the listening time of the first frame, which is formulated as a linear programming problem and solved using the CPLEX tool, as well as predicting the time slot and position of the beacon frame based on the attained information from the frames and the process dormancy when a beacon frame is impossible to come out. Our simulation results show that the proposed methods effectively reduce the energy consumption during neighbour discovery process in a TDMA-based wireless sensor network.

Keywords: wireless sensor networks; IEEE 802.15.4e; neighbour discovery; energy consumption.


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control. It has the special network structures and setup and normal operation, including routing and topology essence of network formation, which regulates network interaction. The neighbour discovery is considered as the synchronisation, neighbour discovery and networking the IEEE802.15.4e protocol also processes time modifying the original IEEE802.15.4 hardware. sleep level and reduce energy consumption without and adopted the time division multiple access (TDMA) and IEEE802.15.4e working group has also redesigned the energy conservation is investigated. Furthermore, the 802.15.4 (IEEE, 2011) specification, the MAC layer for links and plays an important role in the protocol stack in determines the allocation and utilisation of communication dormant process.

transmission speed of the wireless transceiver and the energy consumption mainly by controlling both the methods. It can determine the manner and speed of energy discovery exerts a very positive effect on decreasing earlier the network works. As a result, such neighbour discovery is also a research hotspot in recent years.

In recent years, numerous researchers focus on the establishment of wireless sensor networks especially the development of neighbour discovery. Traditional work concentrates on carrier sense multiple access (CSMA) network, such as an IEEE802.15.4 network which uses single channel (Xiao et al., 2006; Misic et al., 2006, 2008; Musaoliou-E and Terzis, 2008; Krishnamurthy and Sazonov, 2008; Shuaib and Aghvami, 2009; Wang et al., 2009; Coluccia and Ricciato, 2013; Hussain et al., 2014; Lu et al., 2011). The faster the neighbour discovery is completed, the earlier the network works. As a result, such neighbour discovery exerts a very positive effect on decreasing listening time and enhancing energy efficiency.

Single-channel neighbour discovery research can be classified into two approaches as follows. The first approach is called the probability approach (Vasudevan et al., 2009; McGlynn and Borbash, 2001; Kondareddy et al., 2008), which is the used most widely currently. Although the approach improves the listening efficiency to some extent, the reliability of neighbour discovery has always been reduced, and unexpected discovery delay even happens in some extreme circumstance (Dutta and Culler, 2008). The other approach is deterministic neighbour discovery, which significantly improves the reliability of the neighbour discovery, but sometimes increases the discovery time (McGlynn and Borbash, 2001; Dutta and Culler, 2008; Ye et al., 2002; Polastre et al., 2004; So et al., 2006).

Owing to the multi-channel and the frequency hopping mechanisms, a variety of single-channel neighbour discovery methods could not be utilised directly in the IEEE802.15.4e network. One fundamental reason accounts for this point is that multi-channel increases uncertainty by directly adding another dimension of channel search in the searching space, and this also increases the actual completion time significantly. For instance, a simple and practical method from the IEEE802.15.4 called passive discovery (PSV) turns on all available channels for neighbour discovery with the longest lasting time of each

1 Introduction

In recent years, industrial automation makes great progress in many aspects, and therefore, there is a great demand for industrial wireless sensor networks (Lin et al., 2014; Wang et al., 2013; Meng et al., 2010; Liang et al., 2011). Industrial wireless sensor networks must not only be designed to handle the reliability and timeliness, but also need to extend the lifetime given the condition of the battery supply or other non-continuous power (Xiao, 2005; Xiao et al., 2004; Chen et al., 2006; Wang and Xiao, 2006; Wu et al., 2005).

Among many factors that can account for the energy consumption of wireless sensor networks, communication protocol improvement is regarded as one of the significant methods. It can determine the manner and speed of energy consumption mainly by controlling both the transmission speed of the wireless transceiver and the dormant process.

Medium access control (MAC; Zhang et al., 2013) determines the allocation and utilisation of communication links and plays an important role in the protocol stack in terms of energy consumption. As a result, in the IEEE 802.15.4e (IEEE, 2011) specification, the MAC layer for energy conservation is investigated. Furthermore, the IEEE802.15.4e working group has also redesigned the MAC layer in IEEE802.15.4-2006 protocol (IEEE, 2006) and adopted the time division multiple access (TDMA) and the time synchronised channel hopping (TSCH) to enhance sleep level and reduce energy consumption without modifying the original IEEE802.15.4 hardware.

Similar with other general self-organising networks, the IEEE802.15.4e protocol also processes time synchronisation, neighbour discovery and networking interaction. The neighbour discovery is considered as the essence of network formation, which regulates network setup and normal operation, including routing and topology control. It has the special network structures and communication forms that account for the special neighbour discovery process in an IEEE802.15.4e network.

The traditional neighbour discovery is generally divided into either an active way or a passive way. In an IEEE802.15.4e network, nodes achieve neighbour discovery through passively listening the communication messages from the neighbours to avoid conflicting. On one hand, neighbour discovery, which serves as the first step in network operation, needs to be done as quickly as possible so as to achieve the efficient network. On the other hand, due to the energy constraints of low-power applications, how to use the minimum energy to achieve neighbour discovery is also a research hotspot in recent years.

In recent years, numerous researchers focus on the establishment of wireless sensor networks especially the development of neighbour discovery. Traditional work concentrates on carrier sense multiple access (CSMA) network, such as an IEEE802.15.4 network which uses single channel (Xiao et al., 2006; Misic et al., 2006, 2008; Musaoliou-E and Terzis, 2008; Krishnamurthy and Sazonov, 2008; Shuaib and Aghvami, 2009; Wang et al., 2009; Coluccia and Ricciato, 2013; Hussain et al., 2014; Lu et al., 2011). The faster the neighbour discovery is completed, the earlier the network works. As a result, such neighbour discovery exerts a very positive effect on decreasing listening time and enhancing energy efficiency.
channel. However, a lot of time and energy are consumed in the case of the undetermined beacon interval.

For reducing ineffective searching time, the paper Karowski et al. (2011) had successfully investigated a linear programming method to explain the time minimisation of the neighbour discovery based on the multi-channel TDMA network slot communication features. On the basis of the PSV, Karowski et al. (2011) also proposed two useful strategies namely OPT and SWOPT, which reduced the first, average and maximum channel searching time. Nevertheless, those methods only optimise the searching time without taking the energy consumption into account, and this makes them inapplicable to the energy strictly wireless sensor network.

This paper aims to investigate a multi-channel asynchronous neighbour discovery method which exhibits energy sensitive and IEEE802.15.4e-dependent features to promote energy efficiency. In this paper, we propose a novel time and energy-optimised neighbour discovery method based on the paper (Karowski et al. 2011) during the IEEE802.15.4e wireless sensor network process. The simulation results illustrated that this method achieved efficient neighbour discovery with shorter time and less energy consumption.

The rest of the paper is organised as follows. Section 2 presents the network model used in this paper. Section 3 demonstrates the core methods and ideas. Section 4 presents simulation results. Finally, we conclude the paper in Section 5.

2 The network model

In this section, we introduce the network model. Most of the materials and methods in this section are from IEEE 802.15.4e specification (IEEE, 2011, 2012).

2.1 IEEE802.15.4e network

Even though many users prefer to the IEEE802.15.4 protocol, there still exists three drawbacks which limit its application in industrial fields. The first problem is collision. Owing to the utilisation of CSMA communication mechanism, all nodes will compete against each other. As a result, a serious communication collision may take place with the excessive nodes in the network, and this could finally cause unreliable of the network and unpredictable time of communication delay. The second problem is high energy consumption. Wireless routers cannot be dormant when using CSMA, and thus the terminal part will spend a plenty of energy because of the competition and back off. The third disadvantage is interference. The utilisation of a single channel is always susceptible to interference and signal fading effect. From these three issues, the key point could be drawn that if the energy optimisation is regarded as the most serious problem in the network, it is not a good choice in industrial environments.

The IEEE802.15.4e network exerts a positive effect on solving these problems above mainly through the application of TSCH technology. On one hand, the use of time synchronisation and TDMA technology could achieve the schedulable time slot communication, so that each device could carry on sleeping without the RF transceiver during the time slot. As a result, it not only improves the working efficiency, but also reduces energy consumption. On the other hand, channel hopping and black list techniques can effectively avoid the interference of the random noise and continuous noise within a specific frequency to improve communication reliability. Furthermore, IEEE802.15.4e is backward compatible with IEEE802.15.4, and partially maintains the CSMA mechanism.

2.2 Types and formats of LLDN network frame

Low latency deterministic network (LLDN), specified in IEEE 802.15.4e and designed for low-power consumption and deterministic communications, are for deterministic applications in the industrial environment. It has fully slot TDMA structure to support dormancy and multi-channel hopping communication. In this paper, we focus on LLDN.

An LLDN network is a star-type wireless sensor network for ultra-low-power consumption. It contains a coordinator and a plurality of wireless nodes, and each wireless node only communicates with the coordinator.

In the LLDN network, only the coordinator could send the beacon frame. In a superframe cycle, there is only a beacon frame. The structure of superframe is shown in Figure 1.

As is shown in Figure 2, a superframe includes four parts:

- the beacon frame which occupies a time slot, is sent by the coordinator, and is received by other nodes later
- the management slot section which includes uplink and downlink, and plays an important role in network management of the data transmission
- the upstream slot section which is mainly for frame retransmission
- bidirectional communication section for the events of other network frames sent and received, or response.

In the LLDN network with a coordinator and \( m \) nodes, each node has a unique network identity, which contains a transceiver and omni-directional antenna and communicates through half-duplex pattern. Multi-channels are used to communicate in the LLDN network with an available channel set \( C = \{ c_1, c_2, \ldots, c_m \} \), and \(|C|\) represents the number of channels in the collection. In the IEEE 802.15.4e network, the maximum available number within ISM band (2.4 GHz) is 16. The period that coordinator transmits a beacon frame is called beacon interval (BI), which is also the superframe length of the LLDN network. We have
where $b$ equals to beacon order, with a known set, $B = \{b_{\text{min}}, \ldots, b_{\text{max}}\}$, and $|B|$ represents the number of elements; $Z$ represents slot length containing 960 symbol times, and each symbol time is 16 $\mu$s.

Each time slot frame transmission has its own fixed link, which is defined as a four-tuple $(c, t, T, R)$, including channel $(c)$, time slot $(t)$, the transmitted address $(T)$ and a recipient address $(R)$. Owing to the star-type characteristics of the LLDN network, either $T$ or $R$ should be a coordinator address, and all the links will be scheduled by the coordinator and distributed to the relevant node.

Figure 3 demonstrates that the LLDN network frame accord with the basic frame format of IEEE802.15.4e.

There are two bits which mark the frame type in the frame control field, as shown in Table 1.

For any frame captured from the network, the approximate location from the next beacon frame could be deduced based on frame type.

In the auxiliary security header of an LLDN frame, if it contains more than 5 bytes, there must be a frame counter with the value of 5 bytes absolute slot number (ASN), which indicates the number of time slots from the coordinator beginning to work to the current time point. When the coordinator starts working, the first beacon frame will be sent. Therefore, the transmission of the beacon frame slot could be shown below:

\[ \text{BeaconASN \ mod \ } 2^b = 0. \]  

According to the features of the frames, the location could be deduced through analysing any beacon and $b$ value. Since the auxiliary security header is an optional content, not every network can be directly obtained the current value of the ASN in any frame.

### 2.3 Neighbour discovery model for IEEE802.15.4e

Neighbour discovery defines as the acquisition for the beacon frames of the coordinator in the LLDN network. Since each superframe only contains a beacon frame, the target of neighbour discovery is to find the only beacon frame in each superframe. However, new devices are not yet involved in the network, and thus the link does not exist during the neighbour discovery, impeding the transmission of frames and communication. Therefore, the neighbour discovery always undergoes passive monitoring mode.
On the basis of this passive monitoring model, the beacon frame which is sent periodically could be detected by occupying one time slot in each channel every time. If \( t_0 \) represents the starting time slot, for all \( c \in C \), and \( t \in T \), then the binary variable \( x_{ct} \) describes the monitoring result of the channel monitoring nodes \( c \) and time slot \( t \): 

\[
x_{ct} = \begin{cases} 
1, & \text{if discovery is performed on channel } c \text{ at time slot } t, \\
0, & \text{if no discovery is performed on channel } c \text{ at time slot } t. 
\end{cases}
\] (3)

The total record time of neighbour discovery is described as \( t_{\text{max}} = \left| C \right| \times 2^{b_{\text{max}}} - 1 \), given the known \( B \) and \( C \) values, assuming that no beacon has lost.

To obtain the beacon frame during passive monitoring, the following conditions should be met with (Karowski et al., 2011):

- A single channel monitoring time limits so that monitoring time for each channel should not be less than a superframe length:

\[
\sum_{c \in C} x_{ct} \geq 2^{b_{\text{max}}} \quad \forall c \in C.
\] (4)

- Parallel monitoring limits so that the same time slot can only search for a single channel.

\[
\sum_{c \in C} x_{ct} \leq 1 \quad \forall t \in T.
\] (5)

- Slot allocation limits so that all possible combinations of channels and time slots should be found.

\[
\sum_{c \in C} x_{ct} \geq 1 \quad \forall \delta \in (0, \ldots, 2^{b} - 1).
\] (6)

Therefore, without the loss of the beacon frames, neighbour discovery can finally be completed as long as the above conditions are fulfilled with. In addition, the neighbour discovery time is measured from the starting point of neighbour discovery process to the received point of the first beacon frame.

3 The design for energy-efficient neighbour discovery

In the IEEE802.15.4 network, PSV neighbour discovery continuously monitors for a beacon interval (BI) in a single channel, and then switch to another available channel until the beacon frame is ultimately monitored. However, there are two weak points in the case of BI unknown. One is that the monitoring time cannot be determined in a single channel; the other is that the long BI value can cause serious energy consumption.

Karowski et al. (2011) had successfully designed a linear programming method on the assumption that time synchronisation has been completed before the neighbour discovery. Thus, the OPT neighbour discovery method could be obtained by optimising the average monitoring time according to the operation of CPLEX tool. Furthermore, based on the OPT method, an alternative SWOPT neighbour discovery could also be proposed by reducing channel switching time. However, drawbacks also exist in the actual LLDN network. On one hand, the monitoring target is only beacon frame, and other frames are not taken into account. On the other hand, Karowski et al. (2011) only concerned the optimisation of the time without considering energy consumption. In this paper, an optimised method is designed to reduce energy consumption and decrease neighbour discovery time based on the predicted possible Beacon frame position from the frames.

3.1 Time optimised frame capturing method

The location of beacon frame could actually be predicted according to the correlation between beacon frame and general frames. As a result, this general frame-based neighbour discovery could easily be achieved through analysing the messages from numerous general frames. There are several merits deserved to demonstrate. On one hand, there are a large number of general frames which facilitate to initiate the beacon frame listening process. On the other hand, listening to general frames also take shorter time, contributing to enhancing energy efficiency.

In the network parameter setting process, beacon frame sequence \( b \) can be fixed on the basis of the frame capacity. Let \( N \) denote the number of the maximum nodes which can be accommodated in the network. Let \( l \) denote the average number of frames of each node in superframe network. Let \( \text{Const} \) denote the number of frames, which is generally considered as a constant. Since beacon frame also belongs to management frame, thus \( \text{Const} \geq 1 \). Generally, on the condition of the full capacity, it fulfils that

\[
2^{l-1} \leq l \times N + \text{Const} \leq 2^{b}.
\] (7)

Let \( n \) denote the actual number of nodes. When the network construction is not completed or the workload is unsaturated, the frame number \( m \) in one superframe shall be content with the following formula:

\[
m = l \times n + \text{Const} < 2^{b}.
\] (8)

Therefore, the number of frames in one superframe \( m \) could be represented in the function of \( b \) as follows:

\[
m = f(b).
\] (9)

According to (8) and (9), \( f(b) \) can be expressed as below.

\[
f(b) = k \times 2^{b} + \text{Const},
\] (10)

where \( k \) is the coefficient, \( 0 \leq k \leq 1 \).
According to the IEEE802.15.4e, \( f(b) \) is required to meet two extreme conditions. One is that only one coordinator exists, and thus \( f(b) = 1 \), which means only one beacon frame is transmitted by the coordinator in each superframe network. The other is that when network saturation occurs, we have \( f(b) = 2^b \), i.e., each superframe contains \( 2^b \) frames and frame transceiver takes place every time slot.

If there are \( m \) frames in superframe period \( 2^b \) (the number of the frame is \( f(b) \)), then the probability for coming out frames at a certain time slot and the designated channel could be illustrated as follows:

\[
P = \frac{m}{2^b \times \lceil C \rceil^t} = \frac{f(b)}{2^b \times \lceil C \rceil^{(t)}}.
\]  
(11)

In the star-type network, all devices communicate with the coordinator. Therefore, there must be a coordinator in one link. To avoid the conflicts, two links cannot occur simultaneously in the same time slot. As a result, the possible combinations of \( f(b) \) frames satisfy below formula.

\[
C_i = C(2^b, f(b)) \times \lceil C \rceil^{(t)}.
\]  
(12)

In this paper, whenever one frame is detected, the monitoring process will stop. Thus, in order to obtain the probability for the first detected frame at time \( t \), the equation could be illustrated as follows: \( t = d \times x + y \), \( d = 2^b \), and both \( x \) and \( y \) are integers. Therefore, \( x = t/d \) is processed for rounding, and \( y = t \mod d \). If \( 2^b \) is expressed as the cycle, then the number of combinations for coming out the number of frames \( k \) in time slots \( y \) before time \( t \) could be demonstrated as:

\[
C_2 = C(y, k) \times \lceil C \rceil^{(t-1)} \times C(d - y - 1, f(b) - 1 - k) \times \lceil C \rceil^{(t-1)-k}.
\]  
(13)

Therefore, the combination for the frame appears at \( t \) moment to be the first frame accords with the formula below.

\[
C_3 = \sum_{k=0}^{f(b)+1} C_2.
\]  
(14)

Here, we have \( y \geq k \), \( d - y - 1 \geq f(b) - 1 \). At this point, the probability that the frame comes out at \( t \) moment to be the first frame is content with the following formula:

\[
P = C_3/C_1.
\]  
(15)

When \( f(b) = 1 \), the meaning of \( p \) coincides with that in Karowski et al. (2011) on assumption of no frame in the network. If the time slot and channel distribution is random, then the average detection time can be expressed by the number of time slots as follows:

\[
t_{\text{avg}} = \sum_{i = 0}^{C_{\text{max}}} \sum_{j = h_{\text{max}}}^{h_{\text{max}}} \sum_{i_{\text{min}}}^{i_{\text{min}}} \sum_{i_{\text{min}}}^{i_{\text{min}}} \sum_{i_{\text{min}}}^{i_{\text{min}}} u, b_i = b_{\text{min}},
\]  
\[
t_{\text{avg}} = \sum_{i = 0}^{C_{\text{max}}} \sum_{j = h_{\text{max}}}^{h_{\text{max}}} \sum_{i_{\text{min}}}^{i_{\text{min}}} \sum_{i_{\text{min}}}^{i_{\text{min}}} \sum_{i_{\text{min}}}^{i_{\text{min}}} u, b_i > b_{\text{min}}.
\]  
(16)

Here, we have \( u = x \times (t+1) \times \sum_{i=h_{\text{min}}}^{h_{\text{max}}} p \), where \( t+1 \) represents the number of time slot used for listening, and \( t \) starts from zero.

The aim for system optimisation is to minimise \( t_{\text{avg}} \) by linear programming, so that neighbour discovery time will be decreased and the energy consumption will be reduced. The system optimisation is processed in the following three conditions, respectively:

- \( f(b) = 1 \)
- \( f(b) = 0.5 \times 2^b + 1 \)
- \( f(b) = 2^b \) and \( B = \{1, 2\} \), \( C = \{0, 1, 2\} \).

Then, YALMIP (YALIMP, website) is utilised for modelling, and the programming operation has also been achieved through the use of Matlab (Matlab, website) and the invoked CPLEX 12.5 (CPLEX, website). The result is shown in Figure 4(a). Figure 4(b) is the improved algorithm by Karowski et al. (2011), which mainly focuses on decreasing the energy consumption because of the switching channels, and Figure 4(c) depicts the passive listening mode in IEEE802.15.4 network.

As is shown below, the same result comes out compared with the OPT generated by Karowski et al. (2011). Thus, the optimised method in this paper can be marked as E-opt to distinguish from OPT. There are two characteristics of the novel updated algorithm in this paper. First, SWOPT is also a candidate of the solution set. Secondly, It will not increase the energy consumption during switching channels due to the consideration of the internal time slot sleep leading to turning the radio on and off in each time slot, which is different with the case in Karowski et al. (2011) showing that the radio is not closed during the process. Therefore, OPT and SWOPT exerts a similar effect on solving the problem in this paper.

### 3.2 Beacon frame location prediction

According to the IEEE 802.15.4e protocol, the transmission opportunity of beacon frame is the first time slot of each superframe in the LLDN network. Thus, the absolute time slot number is integer multiplication of the superframe length, as is depicted in equation (2).

The range of beacon order can be diminished according to the information obtained from the first frame. Even the location of the beacon frame could also be predicted. If the current ASN of the first frame is depicted as \( \text{ASN}_{\text{current}} \), then its value can be gained through the information from the network directly or indirect prediction.

The essential messages can be acquired from the ordinary frames, which include the following points.
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Figure 4  Distribution of scanning time slots for $|C| = 3$ and $B = \{1, 2\}$: (a) energy optimised (E-opt); (b) SWOPT (Karowski et al., 2014) and (c) IEEE 802.15.4 passive discovery (PSV) (see online version for colours)

The distance between the current and the beacon time slot in superframe is mainly determined by the frame type in the LLDN network. As is illustrated in Table 1, frame can be classified into four types: beacon frame, data frame, acknowledgement frame, and command frame. Nevertheless, acknowledgement frame is not taken into consideration because it can exist in any time slot. Therefore, with the other three types of frames used to predict the time slot position, the following three cases are needed to be discussed according to the frame types.

- If the frame is a beacon frame, neighbour discovery is completed at the moment the beacon is detected.
- If the frame is a command frame, zero or one time slot difference exists between the command frame and the beacon frame in the LLDN network. Thus, the equation can be deduced as follows:

$$1 \leq \text{ASN}_{\text{current}} \mod 2^b \leq 2.$$  \hspace{1cm} (17)

- If the frame is the data frame, the time slots that data frame and beacon frame located in do not coincide with each other because of the broader location of the data frame. Thus, it can be expressed that

$$\text{ASN}_{\text{current}} \mod 2^b \neq 0.$$ \hspace{1cm} (18)

According to equations (17) and (18) together with equation (2), the range of $b$ can be ultimately determined.

The information of frame listening time can be utilised to narrow the range of $b$, which is expressed as:

$$2^b > t.$$  \hspace{1cm} (19)

In the frame containing auxiliary security header with no <5 bytes, the frame count can be easily obtained. Furthermore, the value of the frame count equals to $\text{ASN}_{\text{current}}$.

The position of the beacon frame can be easily predicted according to the value or the range of $\text{ASN}_{\text{current}}$. Thus, a time slot set called $TB$ can be established, including all possible time slots in which the beacon frame can appear. Therefore, the elements $t$ in $TB$ accords with the following equation:

$$T - t_{\text{current}} = \text{ASN}_{\text{beacon}} - \text{ASN}_{\text{current}}.$$ \hspace{1cm} (20)

Here, we have $\text{ASN}_{\text{beacon}} > \text{ASN}_{\text{current}}$. According to the information from $TB$, the opportunity of the appearance of the beacon can be predicted, so that the listening process only starts in the time slots in which beacons may appear. In contrast, when beacon does not come out, dormancy takes place in order to reduce the power consumption. Even though no frame is detected, the range of $b$ could also be further narrowed.

On the basis of the three conditions above, the possible appeared time slot of beacon frame is capable of being fixed reasonably and accurately to a great extent, which can not only detect the beacon easily, enhance the listening efficiency, but also reduce energy consumption caused by the blind listening. As a result, combined with the first frame detection method, a novel optimised neighbour discovery method is attained with the efficiency enhancement of the energy utilisation.

3.3 Energy optimised neighbour discovery

According to the frame detection method and the location prediction of the beacon frame discussed above, neighbour discovery algorithm is stated as follows:

- **Step 1**: Design the frame monitoring algorithm E-opt according to the results from CPLEX tool, and begin to listen through selecting any time slot as a starting point.
- **Step 2**: Record $\text{ASN}_{\text{current}}$, the frame type and the number of time slots from the beginning to the current point after detecting the first frame. Then, calculate the
nearest time slot $t_{cal}$ that the beacon frame may appear according to equations (2), (17)–(19).

- **Step 3**: Keep dormant until the time slot $t_{cal}$.
- **Step 4**: Listen to the specific channel in time slot $t_{cal}$. Channel value is calculated by E-OPT algorithm.
- **Step 5**: If the beacon is detected, stop listening. Thus, neighbour discovery is completed. If not, then return to **Step 2** and continue to process listening till the beacon is detected.

4 Simulation

The simulation was conducted using Matlab based on the actual situation. Two scenes were considered, namely the changing number of frames and the changing sequence of the beacons. Under these two scenes, E-opt, SWOPT and PSV methods were tested, respectively. As a result, several key factors were evaluated such as the average time for searching the first frame, the time slot number of the beacons, as well as the effect of different frame number on the average time for monitoring the first frame.

The network parameters are set in Table 2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Symbol duration</td>
<td>16us</td>
</tr>
<tr>
<td>Time slot duration</td>
<td>960 symbols</td>
</tr>
<tr>
<td>Channel set C</td>
<td>${0, 1, 2, 4, 5, 6, 7}$</td>
</tr>
<tr>
<td>Beacon order set B</td>
<td>${2, 3, 4, 5}$ or ${8, 9, 10}$</td>
</tr>
</tbody>
</table>

4.1 Time comparison for the first frame detection under different beacon sequence

According to the previous analysis, E-opt and SWOPT hold the same average detection time when $BI$ value changes. Thus, the average detection time for the first frame was compared in this paper.

Here, $b_{\text{max}} = 2$, $b_{\text{min}} = 5$, the variable circumstances of $BI$ (namely 2, 3, 4, 5), the first frame detection time is calculated under both E-opt and PSV ways. $f(b)$ depicts the number of frames in this case and is set to 1,2,3,4.

As was illustrated in Figure 5, the first frame detection time is enhanced when $BI$ increases, suggesting that a larger superframe length requires a longer detection time. Meanwhile, when under the case of same number of frames ($f(b)$ same), E-opt generally spends a shorter detection time than that of PSV, and the smaller the $BI$ is, the more obviously the results appears. When $BI$ value reaches to $b_{\text{max}}$, E-opt and PSV cost the same.

4.2 Effect of the number of frames on frame detection time of OPT method with $BI$ fixed condition

Here, $B = \{4, 5\}$, and the average frame capture time is calculated when the frame number is increased from 1 to 16.

Figure 6 demonstrated that the average detection time decreases when the number of frames is increased. This mainly is due to the increased probability of emerged frames when the number of frames is increased. Therefore, the average detection time is shortened due to the increased probability for capturing frames. As illustrated in the Figure 6, the increased normal frame detection can significantly reduce the listening time. However, the effect appears less obvious with the more frames captured.

4.3 Comparison of energy consumption during beacon frame detection

The number of frames in unit time correlates with the number of nodes, suggesting that four frames are added by one superframe when one node joins in the network. Thus, when $B$ is fixed in $\{8, 9, 10\}$, the energy consumption rate is calculated in case of the node number from 0 to 20 by using the E-opt, SWOPT and PSV, respectively. Suppose that the same energy is consumed in each time slot in undormant circumstance, and is called unit energy. If dormancy happens, the energy consumption in time slot is zero. Thus, the consumed energy could be expressed by the energy consumed in each time slot multiplied with the activity time slot number. The value of energy consumption is equal to the value of the activity time slot.
number. Thus, the single time energy consumption is shown in Figure 7.

**Figure 7** Single time energy consumption (see online version for colours)

As is shown in Figure 8, along with the increased number of nodes, the energy consumption detected by E-opt is reduced gradually. However, for SWOPT and PSV, the energy consumption is not related to the number of nodes. In principle, the total beacon detection time of these methods should be identical. But for E-opt method, it is the dormancy which depends on the information obtained from the surrounding frames that leads to enhancing the efficiency of energy utilisation. Additionally, from the cumulative effect of E-opt method, when a certain number of nodes accumulate in the network, the energy consumption of the new involved nodes can almost be negligible when compared with the other SWOPT and PSV methods.

From what has been discussed above, the conclusion we can draw is that the E-opt method significantly reduces the energy consumption during neighbour discovery process. Thus, it can widely be applied in some energy-dependent circumstances such as battery-powered and the obtained energy from the environment cases.

**Figure 8** Total energy consumption (see online version for colours)

5 Conclusion

This paper proposes a novel neighbour discovery method for energy optimisation in the IEEE802.15.4e network, and not only achieves the frame listening in an ordinary way instead of the passively listening manner, but also forecasts the opportunity for transmitting the beacon frames according to the frame counter. To reduce passive listening time, the linear programming model is also established, and this finally contributes to the design of the scheduling sequence by using CPLEX tool. Therefore, the neighbour discovery proposed in this paper exerts a very positive effect on decreasing passive listening time and enhancing energy efficiency.

Nevertheless, the task can only be processed on the assumption of node synchronisation without considering the effects of unsynchronised on discovering time. Additionally, the method in this study considers that only one node can transmit beacon periodically in the LLDN network. The next step of this study is how to achieve the fast neighbour discovery on the condition that the nodes are not synchronised, as well as multi-channel neighbour discovery in case of multi-beacon frames.

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