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# SBA: An Efficient Algorithm for Address Assignment in ZigBee Networks

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**Abstract** ZigBee Specification defines a distributed address assignment mechanism (DAAM) for assigning addresses to nodes in ZigBee networks. However, some nodes are likely not to get addresses as DAAM limits the number of child nodes of a router in advance. To address this problem with the spare addresses that DAAM does not use, we first derive an upper bound of the probability that DAAM exhausts the 16-bit address space, and then propose a segmentation-based algorithm (SBA) for on-demand scalable address assignment in ZigBee networks. Through segmenting the 16-bit address space according to the maximum address predefined by DAAM, SBA enables a router to use the addresses in new space segments if it has insufficient addresses to accommodate child nodes. In addition, the tree routing protocol is improved to suit extended addresses. Performance analysis and numerical results reveal that SBA outperforms DAAM and its two improvement versions in terms of the success rate of address assignment, communication overhead, and the average time spent to assign an address.

**Keywords** Wireless sensor networks · ZigBee Specification · Address assignment · Algorithms · Segmentation

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## 1 Introduction

The distributed address assignment mechanism (DAAM) [1] is a fundamental scheme for assigning addresses to nodes in wireless sensor networks [2,3] that adopt the ZigBee technology [1,4–6]. It utilizes the following three parameters to assign addresses: (1) the maximum number of child nodes, say $C_m$, (2) the maximum number of child routers, say $R_m$, and (3) the depth of the network, say $L_m$. Since the assigned addresses contain the "parent-children" relationships, DAAM sets up implicit routes for all source-destination pairs. Through computation with the destination address, an intermediate node can know the next hop without looking up its routing table. This is the key idea of the tree routing (TR) protocol [1,7,8]. Thanks to the simplicity and effectiveness, DAAM is extensively studied and put into use in the last few years.

However, due to the diversity of network context, the predetermined parameters $C_m$ and $R_m$ cannot always satisfy the requirement for address assignment, which leads to that some nodes cannot attain network addresses and become orphan nodes [9]. For convenience, we call the orphan problem caused by the limitation of $C_m$ or $R_m$ an insufficient breadth (IB) problem. Figure 1 shows an example of this problem, in which node $A$ cannot get its address due to the limitation of $C_m$. The IB problem will make some nodes lack network addresses and separate from ZigBee networks, especially in case of a high density of nodes. To explore the impact of the IB problem, we conduct seven simulation experiments according to the settings in Fig. 2 of [9]. From the related results listed in Table 1, we can see that regardless of different $(R_m, L_m)$ combinations, there always exist 9.4–83.3 % orphans incurred by the IB problem.

A multitude of works have investigated the IB problem. In [9], the orphan problem is examined and some solutions are put forward. However, these solutions need to repeatedly generate several trees and to truncate some nodes from these trees, which incurs a great deal of control overhead. In the schemes of [10,11], when a node's address space becomes insufficient, it borrows addresses from other nodes which have spare addresses. In addition to incurring the extra communication overhead, these schemes also damage the "address-position" relationship created by DAAM. Based on DAAM, an on-demand method, hybrid address configuration (HAC) is presented in [12] for nodes to request addresses from the coordinator, in which the coordinator assigns the addresses that DAAM never uses to the requestors. A similar method introduced in [13] uses the addresses or address blocks not occupied by DAAM to accommodate more nodes. However, it conducts address reassignment only once. Likewise, the methods in [12,13] may cause extra communication overhead

**Table 1** Percentages of orphans incurred by the IB problem (are denoted as IB-orphans) and delays under different combinations of $(R_m, L_m)$

| $(R_m, L_m)$ | All orphans | IB-orphans | Ratio of IB-orphans | Delay(s) |
|---|---|---|---|---|
| (6,2) | 32 | 3 | 9.4 % | 0.0898 |
| (5,3) | 21 | 8 | 38.1 % | 0.1717 |
| (4,4) | 10 | 6 | 60 % | 0.2046 |
| (3,5) | 9 | 7 | 77.8 % | 0.2402 |
| (2,6) | 10 | 8 | 80 % | 0.2955 |
| (3,7) | 5 | 3 | 60 % | 0.3622 |
| (2,8) | 6 | 5 | 83.3 % | 0.4108 |

and damage to the “address-position” relationship. Giri and Roy [14] presents a single level address reconfiguration scheme (SLAR), which enlarges nodes’ sub-address space by increasing the value of their depth. When a node at depth $d$ needs extra addresses for its children, it initializes a process of address reconfiguration, in which the parameter $C_{skip}(d+1)$, instead of $C_{skip}(d)$, is used as the gap between the addresses of child nodes. $C_{skip}(d)$ is a variable in DAAM and can be calculated by

$$C_{skip}(d) = \begin{cases} 1 + C_m(L_m - d - 1), & \text{if } R_m = 1 \\ \frac{1+C_m-R_m-C_m R_m{}^{(L_m-d-1)}}{1-R_m}, & \text{otherwise} \end{cases} \tag{1}$$

According to Lemma 1 we prove below, $C_{skip}(d+1)$ is less than $C_{skip}(d)$, thus SLAR makes a node accommodate more child nodes. However, it decreases the depth of the network and incurs extra communication overhead.

To address the IB problem while overcoming the above disadvantages of existing schemes such as extra communication overhead and damage to the “address-position” relationship, we propose a segmentation-based algorithm (SBA) for on-demand scalable address assignment in ZigBee networks, and improve the TR protocol. The main contributions of this paper are (1) an upper bound of the probability that DAAM exhausts the 16-bit address space, (2) a novel algorithm which extends routers’ address spaces without incurring extra communication overhead, and (3) an improved TR protocol to adapt to the extended addresses assigned by the novel algorithm.

The rest of this paper is organized as follows. Section 2 introduces the network model. In Sect. 3, our proposed algorithm is presented in detail. The improved TR protocol is described in Sect. 4. Section 5 provides performance evaluation and compares our algorithm with other three algorithms. Finally, concluding remarks are given in Sect. 6.

## 2 Network Model

In this section, we give the mathematical model of ZigBee networks and related definitions and assumptions which are used below. Moreover, we derive the maximum number of addresses assigned by DAAM and the probability that DAAM exhausts the 16-bit address space. Note that in DAAM the minimum address is 1 and the gap between two neighboring address values is also 1, thus the maximum address is equal to the maximum number of addresses.

### 2.1 Mathematical Model of ZigBee Networks

A ZigBee network can be represented by a graph $G_r = (V_r, E_r)$, where $V_r$ contains all devices and the coordinator, and $E_r$ consists of all symmetric communication links between the nodes in $V_r$. Using the three parameters of DAAM, $C_m$, $R_m$, and $L_m$, the goal of our proposed algorithm is to assign identifications (i.e., network addresses) and “parent-child” relationships to as many nodes as possible.

**Definition 1** An address space denotes a set of addresses composed of some bits. For example, the 16-bit address space consists of all 16-bit addresses and its capacity is $65{,}535(2^{16}-1)$.

**Definition 2** Segmentation denotes dividing an address space into some sub-spaces which contain fewer addresses.

**Assumption** All nodes have the same communication range. This assumption avoids the problem of unidirectional links caused by asymmetric communication ranges.

### 2.2 Maximum Value of an Address Assigned by DAAM

In this section, we calculate the maximum value of an address assigned by DAAM. To this end, we first prove the following three lemmas.

**Lemma 1**

$$C_{skip}(d) > C_{skip}(d+1) \tag{2}$$

*Proof* Note that $C_m \geq 1,\ R_m \geq 1$, and $L_m \geq 1$. Consider the following two cases:

(1) $R_m = 1 : C_{skip}(d) - C_{skip}(d+1) = C_m > 0$.

(2) $R_m > 1 : C_{skip}(d) - C_{skip}(d+1) = \frac{C_m R_m^{(L_m-d-2)} - C_m R_m^{(L_m-d-1)}}{1-R_m} = C_m R_m^{(L_m-d-2)} > 0$.

In both cases, we have $C_{skip}(d) > C_{skip}(d+1)$.

**Lemma 2** *Let $A_p(d)$ denote the address of a parent node at depth $d$. $R_n(d)$ and $E_n(d)$ are the addresses of the $n$th child router and $n$th child end device of the parent node, respectively. Then,*

$$E_1(d) > R_n(d), \quad 1 \leq n \leq R_m \tag{3}$$

*Proof* According to the ZigBee Specification ([1], Page 371), $E_1(d)$ is given by

$$E_1(d) = A_p(d) + C_{skip}(d)R_m + 1 \tag{4}$$

Then we have

$$\max R_n(d) = R_{R_m}(d) = A_p(d) + C_{skip}(d)(R_m - 1) + 1 \tag{5}$$

Clearly, $E_1(d) > \max R_n(d)$. Thus, $E_1(d) > R_n(d),\ 1 \leq n \leq R_m$.

**Lemma 3**

$$E_1(d) > E_n(d+1), \quad 1 \leq n \leq C_m - R_m \tag{6}$$

*Proof* The maximum value of $E_n(d+1)$ can be calculated as follows:

$$\begin{aligned} \max E_n(d+1) &= \max A_p(d+1) + C_{skip}(d+1)R_m + C_m - R_m \\ &= A_p(d) + C_{skip}(d)(R_m-1) + 1 + C_{skip}(d+1)R_m + C_m - R_m \end{aligned} \tag{7}$$

Then

$$E_1(d) - \max E_n(d+1) = C_{skip}(d) - C_{skip}(d+1)R_m - C_m + R_m \tag{8}$$

Consider two cases:

1) $R_m = 1$:

$$\begin{aligned} C_{skip}(d) - C_{skip}(d+1)R_m - C_m + R_m &= 1 + C_m(L_m - d - 1) \\ &-[1 + (L_m - d - 2)] - C_m + 1 = 1 > 0 \end{aligned}$$

It follows that $E_1(d) > \max E_n(d+1)$. Thus, $E_1(d) > E_n(d+1)$.

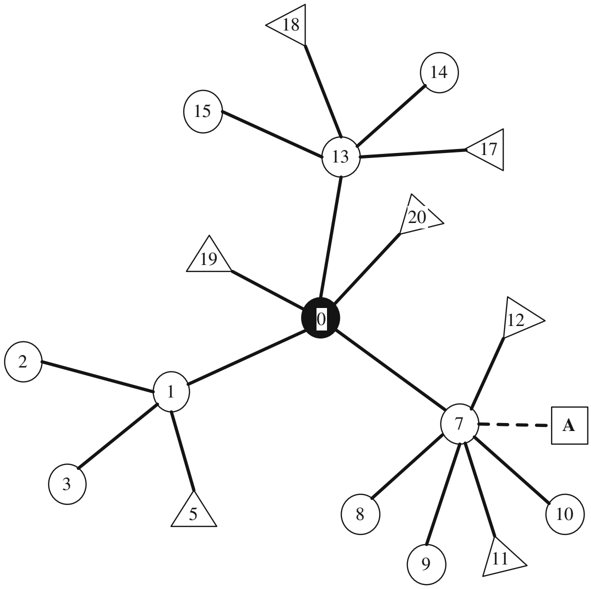


**Fig. 1** The IB problem ($C_m = 5$, $R_m = 3$, $L_m = 2$). *Filled circle* Coordinator, *open circle* router, *triangle* end device, *square* nodes without addresses, *solid line* links in ZigBee networks, *dashed line* links out of ZigBee networks

2) $R_m > 1$:

$$C_{skip}(d) - C_{skip}(d+1)R_m - C_m + R_m = \frac{1 + C_m - 2R_m - C_m R_m + R_m^2}{1 - R_m}$$
$$-C_m + R_m = 1 > 0$$

which implies that $E_1(d) > E_n(d+1)$.

Given the above lemmas, we can compute the maximum value of an address assigned by DAAM, denoted henceforth by $A_m$, which is equal to $E(C_m - R_m)(0)$. Specifically,

$$A_m = E(C_m - R_m)(0) = C_{skip}(0)R_m + C_m - R_m \tag{9}$$

As an example, the maximum value of an address in Fig. 1 is $6 \times 3 + 5 - 3 = 20$.

Undoubtedly, the settings of $C_m$, $R_m$, and $L_m$ need to ensure that $A_m$ is a 16-bit address, i.e., an address which is no more than 65,535.

## 2.3 Probability of DAAM Exhausting 16-Bit Address Space

We observe that DAAM hardly exhausts the 16-bit address space, which means that there is a remaining space for extending the original address space to accommodate more nodes in most cases. To verify the above observation, we derive the probability that the 16-bit address space is exhausted by DAAM below.

Using the maximum number of addresses DAAM assigns, $A_m$, we know that the address space determined by DAAM is equal to $\{1, A_m\}$. Clearly, if DAAM exhausts the 16-bit address space, then $A_m$=65,535. We consider two cases as follows:

(1) $R_m = 1$
We have

$$A_m = [1 + C_m(L_m - 1)] \times R_m + C_m - R_m = C_m L_m = 65{,}535 \tag{10}$$

Through factorization, we get: $65{,}535 = 3 \times 5 \times 17 \times 257$. Then the number of combination $(C_m, L_m)$ is $\sum_{i=0}^{4} C_4^i = 16$.

(2) $R_m > 1$
We have

$$A_m = \frac{1 + C_m - R_m - C_m R_m^{(L_m-1)}}{1 - R_m} \times R_m + C_m - R_m = \frac{C_m \left(R_m^{L_m} - 1\right)}{R_m - 1} \tag{11}$$

Let $\frac{C_m(R_m^{L_m}-1)}{R_m-1} = 65{,}535$. Then

$$R_m^{L_m} = \frac{65{,}535}{C_m/(R_m - 1)} + 1 \tag{12}$$

Taking into account the constraints $R_m > 1,\ C_m \geq R_m$, and $L_m \geq 1$, we perform a traversal search on the combinations of $C_m,\ R_m$, and $L_m$ and find three combinations which satisfy Eq. 12, namely, (4,369, 2, 4), (13,107, 4, 2), (21,845, 2, 2). Thus, based on the above derivation, we obtain the total number of the combinations that exhaust the 16-bit address space: $16 + 3 = 19$.

In addition, we design an algorithm to compute the number of cases of address assignment on the condition of $R_m = 1$, which is detailed as follows.

**Algorithm**: (computing the number of cases of address assignment on the condition of $R_m = 1$)

```
(1)  Initialization: $A_m = 1$, $case\_nb = 0$, $i = 0$;
(2)  $case\_nb + 1 \rightarrow case\_nb$;   //$A_m = 1$
(3)  $A_m + 1 \rightarrow A_m$;
(4)  $case\_nb + 2 \rightarrow case\_nb$;   //$A_m > 1$
(5)  $i = 1$;   //check if $A_m$ can be factorized
(6)  $i + 1 \rightarrow i$;   // $i$ increases from 1
(7)  If $i \geq A_m$, go to Step (10);
(8)  If $A_m \% i \neq 0$, return to Step (6); //$A_m$ cannot be factorized
(9)  If $A_m \% i = i$, $case\_nb + 1 \rightarrow case\_nb$; otherwise $case\_nb + 2 \rightarrow case\_nb$; //$A_m$
     can be factorized
(10) If $A_m < 65{,}535$, return to Step (2); otherwise stop.
```

By running the above algorithm, we obtain the number of cases of address assignment on the condition of $R_m = 1$, which is 1,342,591.

In addition, the number of cases of address assignment on the condition of $R_m > 1$ is more than 1. Thus, the total number of cases of address assignment is more than $1{,}342{,}591 + 1 = 1{,}342{,}592$. Therefore, the probability that DAAM exhausts the 16-bit address space, say $P_e$, is upper bounded by

$$P_e < 1.42 \times 10^{-5} \tag{13}$$

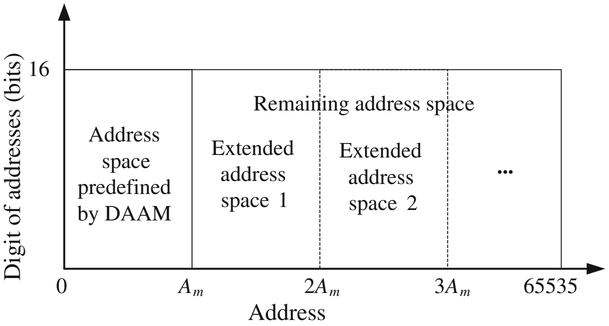


**Fig. 2** Segmentation of the 16-bit address space of ZigBee networks

where $1.42 \times 10^{-5} \approx \frac{19}{1342592}$. As shown in the inequality (13), the probability $P_e$ is very small.

## 3 Proposed Address Assignment Algorithm

According to our observation and the above derivation, DAAM hardly exhausts the 16-bit address space, which means that some addresses are never used. Thus, in order to utilize these spare addresses, we propose an SBA algorithm, which segments the 16-bit address space and extends a router's address space to a new address segment when the address space is insufficient for child nodes, as shown in Fig. 2. The operations of SBA are described below.

### 3.1 Operations of SBA

SBA consists of three main steps, namely, initialization, address request, and address assignment based on space-segmentation, which are detailed as follows.

**Step 1** (Initialization): At the initial time, the coordinator sets itself address to 0 and defines parameters $C_m$, $R_m$, and $L_m$. Then, it puts the above parameters and its depth (equal to 0) into a networking message and broadcasts the message.

**Step 2** (Address Request): Upon reception of the networking message, a node first saves the sender's address in its neighbor table. If the node has no address, it sends a request message to the neighbor which has the minimal depth to apply for an address.

**Step 3** (Address Assignment Based on Space-segmentation): If an addressed router receives a request message, it will assign an address to the requester. We design the following equation for a router with address $A_p$ to work out the $n$th address, $Ar$, for one of its child nodes.

$$Ar = \begin{cases} A_S A_m + A_p + C_{skip}(d)(n-1) + 1, & \text{if router} \\ A_S A_m + A_p + C_{skip}(d) R_m + n, & \text{otherwise} \end{cases} \tag{14}$$

where $As$ is the segment address, which is equal to the times of extending the node's address space. $d$ denotes the router's depth and $C_{skip}(d)$ can be computed with Eq. 1. $A_m$ is the maximum number of addresses assigned by DAAM, which is computed according to Eq. 9.

When the addresses in a router's present address space are insufficient for child nodes, the router extends its address space to a new address segment. Accordingly, the parameter $A_S$ is increased by 1.

After a router gets an address, it puts its address and depth, $C_m$, $R_m$, and $L_m$ into a networking message and broadcasts the message.

Using the above processes, SBA allows more nodes to obtain addresses without incurring extra communication overhead. For example, node $A$ in Fig. 1 cannot get a address based on DAAM, whereas it gets the address 28 ($1 \times 20 + 7 + 1 \times 0 + 1 = 28$) according to Eq. 14 defined by SBA.

### 3.2 Complexity of SBA

We have the following lemma about the complexity of SBA.

**Lemma 4** *SBA and DAAM have the same complexity.*

*Proof* In DAAM, the storage overhead is mainly spent for neighbors' information, and then its storage complexity is $O(N_m)$, where $N_m$ denotes the maximum degree of nodes. SBA only needs to save one extra parameter, namely the segment address, which usually occupies several bits. Thus, the storage complexity of SBA is also $O(N_m)$. The operation time of SBA is defined by the depth of the network and the maximum degree of nodes, so its time complexity is $O(L_m + N_m)$, which is equal to that of DAAM. The communication complexity of DAAM is determined by the depth of the ZigBee network and the degree of routers. Thus, it is equal to $O(NR_m^{L_m-1})$, where $N$ is the average degree of routers. In SBA, the communication overhead is also decided by the depth of the ZigBee network and the degree of routers. Therefore, the communication complexity of SBA is $O(NR_m^{L_m-1})$, which is the same as that of DAAM. Following the above discussions, we conclude that SBA and DAAM have the same complexity.

## 4 Improved TR

TR is a proactive routing protocol defined in the ZigBee Specification, which depends on the addresses assigned by DAAM and conducts routing without any communication overhead. Since SBA extends routers' address spaces, neither TR nor its recent improvements [7,8] can directly process the extended addresses assigned by SBA. Thus, we modify TR to use the extended addresses to compute next-hop addresses. The main steps of the improved TR protocol are given below.

**Step 1**: When a router with address $A$ receives a data packet destined to address $D$, it first calculates the basic destination address, $D'$, by

$$D' = [(D-1) \bmod A_m] + 1 \tag{15}$$

**Step 2:** Use the following inequality to determine if the destination is one of its descendants.

$$A < D' < A + C_{skip}(d-1) \tag{16}$$

If the inequality (16) is true, go to step 3; otherwise, forward the data packet to its parent, then stop.

**Step 3**: Determine if the destination is an end device, by

$$D' > A + R_m C_{skip}(d) \tag{17}$$

If the inequality (17) is true, the next-hop address, $N$, is equal to $D$; otherwise

$$N = A + 1 + \left\lfloor \frac{D' - (A+1)}{C_{skip}(d)} \right\rfloor \times C_{skip}(d) \tag{18}$$

**Step 4**: Forward the data packet to the next hop with address $N$.

## 5 Performance Evaluation

In this section, we perform theoretical analysis and a series of simulation experiments to investigate the performance of our proposed algorithm.

### 5.1 Theoretical Analysis of Main Statistics

We select three statistics, the success rate of address assignment, communication overhead, and the time spent to assign an address, which are defined and analyzed as follows.

### *5.1.1 Success Rate of Address Assignment*

The success rate of address assignment, say $S$, is used to evaluate the effectiveness of an address assignment algorithm. It is defined by

$$S = \frac{N_a}{N} \tag{19}$$

where $N$ and $N_a$ denote the total number of nodes and addressed nodes, respectively. As SBA allows more nodes to get addresses, $N_a$ will increase. Accordingly, $S$ will also increase.

### *5.1.2 Communication Overhead*

Communication overhead expresses the cost spent for communication, and has a negative relationship to the efficiency of an algorithm. Communication overhead can be denoted by $B$, the number of bits in all control packets. We have

$$B = \sum_i L_i \tag{20}$$

where $L_i$ denotes the length of the $i$th control packet. Since SBA reduces the request packets sent by nodes without addresses, the value of $i$ accordingly decreases. As a result, the value of $B$ tends to decrease.

### *5.1.3 Average Time Spent to Assign an Address*

The average time spent to assign an address, say $T$, expresses the time for obtaining an address, which is given by

$$T = \frac{T_s}{N_a} \tag{21}$$

where $T_s$ denotes the time spent for assigning addresses to all addressed nodes. In SBA, more nodes can get their address and fewer nodes need to request address repeatedly, which makes $N_a$ increase and $T_s$ tend to decrease. Thus, the value of $T$ will decrease.

### 5.2 Simulation Results and Analysis

A series of simulation experiments are conducted to quantitatively explore the performance of SBA, in which DAAM [1], HAC [12], and SLAR [14] are selected for comparison. The reason for selecting HAC is that it utilizes the addresses not occupied by DAAM. SLAR is chosen because it particularly addresses the IB problem with address reconfiguration. Numerical results are presented to corroborate our theoretical analysis, and to verify the effectiveness and validity of SBA.

The simulation is conducted with the optimized network engineering tool (OPNET) [15, 16] over Windows XP. $N(N \in \{100, 200, 300, 400, 500\})$ nodes are randomly and evenly deployed in a circular area with a radius of 200 m. IEEE802.15.4a standard [17] is adopted for setting nodes' MAC layer and physical layer, and the communication range of nodes is uniformly 35 m. The proportion between routers and end devices is 6:4. The default values of $C_m$, $R_m$, and $L_m$ are 5, 3, and 8, respectively. Through setting the value of the random seed to 128, 130, 132, and 134, each experiment is performed four times, and the average values of results are used for analysis.

#### *5.2.1 Performance of Address Assignment*

In the first set of experiments, we vary the number of nodes from 100 to 500 in the aforementioned circular area. The performance of address assignment are compared, which includes the success rates of address assignment, communication overhead, and the average time spent to assign an address.

Figure 3 reveals that SBA has the highest success rate of address assignment in each scenario, which is about 84.5 % on average. The reason is that SBA successfully relieves the IB problem. DAAM does not consider the IB problem and SLAR addresses it at the cost of decreasing the network depth, thus their success rates are degraded. Using the method of borrowing addresses, HAC can effectively address the IB problem, so its success rate is almost equal to that of SBA in each scenario. From the figure we see that SBA and HAC cannot eliminate all orphan nodes. This is because some orphan nodes are incurred by the insufficient network depth and the lack of neighboring routers. In addition, we also see that the more the nodes, the more notable is the advantage of SBA. This tendency results from that the IB problem will make more nodes lack addresses when the density of nodes increases.

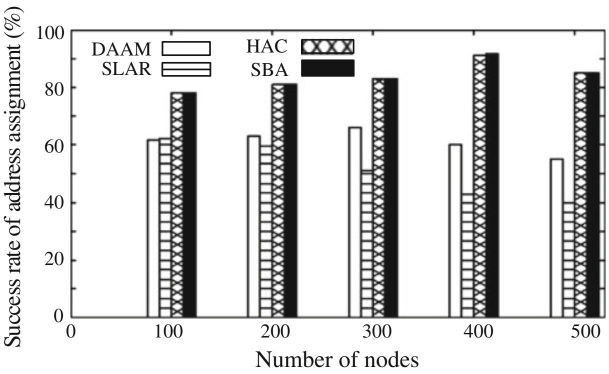


**Fig. 3** Comparison on the success rates of address assignment

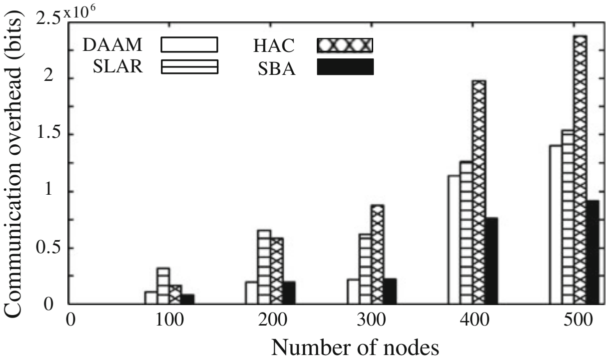


**Fig. 4** Comparison on the communication overhead

Both SBA and HAC achieve their highest success rates in the 400-node scenario, which indicates that with the present settings they are suitable for a ZigBee network consisting of 400 nodes.

In Fig. 4, we observe that SBA has the least communication overhead in each scenario. The average communication overhead of SBA is 347187 bits, which is much less than those of DAAM (489839 bits), SLAR (700718 bits), and HAC (956222 bits). The reason lies in that SBA does not need any extra control messages as compared to DAAM, whereas SLAR and HAC cannot perform like this. They conveys quantities of extra control messages in the reconfiguration process and the process of borrowing addresses, respectively. Thus, their communication overheads obviously increase. The figure also shows that the more the nodes, the larger are the communication overheads of all four algorithms. This is because assigning an address needs to convey at least two control messages. The reason for DAAM underperforming SBA is the repeated requests sent by nodes without addresses. SBA can assign addresses to more nodes, thus fewer nodes need to send multiple requests. As a result, the communication overhead of SBA is about 29 % lower than that of DAAM.

Figure 5 shows that SBA achieves the minimum average time spent to assign an address in each scenario. The average value of SBA is about 0.1 s, which is less than those of DAAM (0.15 s), SLAR (0.44 s), and HAC (0.11 s). The reason is that SBA assigns addresses to more nodes while avoiding extra communication process. Due to the time-consuming reconfiguration process and a low success rate of address assignment, SLAR spends the most average time to assign an address. HAC needs extra time to borrow addresses, but it makes more nodes get addresses. Thus, the average time of HAC is only a little higher than that of SBA. The nodes without addresses are likely to request addresses repeatedly and there are more such nodes in DAAM, thus the average spent time of DAAM is more than that of SBA. As the number of nodes increases, the average time required to assign an address decreases on the whole. This is because addresses can be simultaneously assigned to different nodes.

### *5.2.2 Success Rate of Data Transfer*

In the next set of experiments, we investigate the performance of the improved TR protocol. The number of nodes varies from 100 to 500 in the same circular area, and the success rate of data transfer is selected as the statistic because the direct benefit of the improved TR protocol is to allow more data packets to reach their destinations. In addition, SBA cooperates with the improved TR protocol as it can provide the extended addresses. From the simulation results

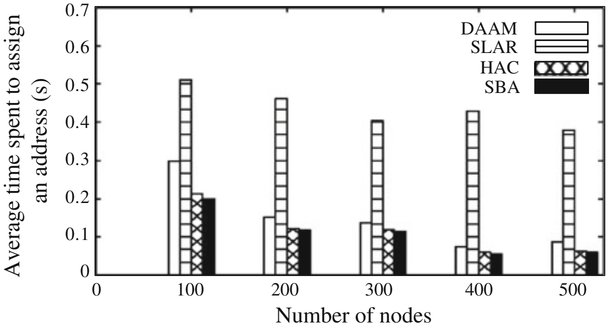
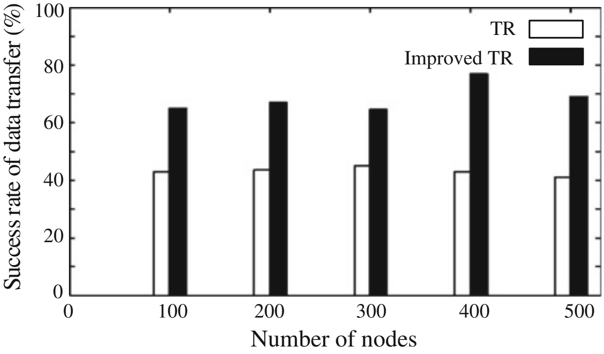


**Fig. 5** Comparison on the average time required to assign an address

**Fig. 6** Comparison on the success rates of data transfer



shown in Fig. 6, we observed that the success rate of the improved TR protocol is higher than that of TR in each scenario. Their difference is between 43 and 79 %. The reason is that the improved TR protocol successfully convey more data packets to their destinations as compared to TR. The maximum success rate is only 77 %, because neither SBA nor DAAM can assign addresses to all nodes. The destinations of data packets are randomly selected. Thus, when nodes without network addresses (they can have other addresses, such as a MAC address) are selected as destinations, the routing of the related data packets fails.

### *5.2.3 Impact of Ratio of Routers and Network Depth*

In a ZigBee network, routers play a key role in assigning addresses. Likewise, the setting of the network depth parameter is important for SBA. Thus, we perform the third set of experiments to illustrate the impact of the ratio of routers and the network depth parameter on the performance of SBA. The number of nodes is 500 and the ratio of router is 60 %. The simulation results in Fig. 7 show the impact of the ratio of routers. When the ratio of routers increases from 20 to 100 %, the success rate of assigning addresses increases from 4.2 to 86.4 %. The reason is that routers have the ability of assigning addresses, thus more routers can accommodate more child nodes. However, since routers can usually occupy only a part of the address space of ZigBee networks, the success rate of address assignment drops when all nodes are routers. On the other hand, the average spent time decreases from 0.39 to 0.05 s when the ratio of routers increases. This is because SBA assigns addresses to more nodes and different nodes can get addresses simultaneously.

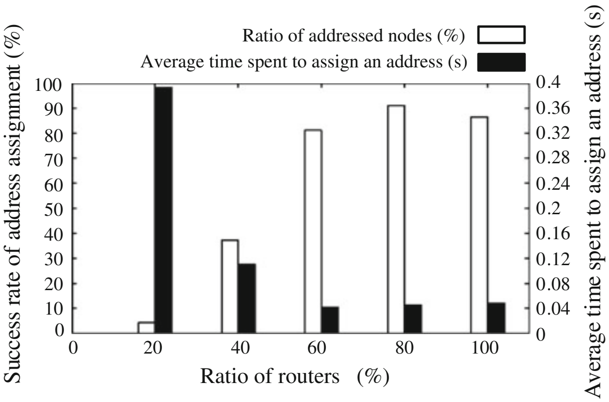


**Fig. 7** Impact of the ratio of routers

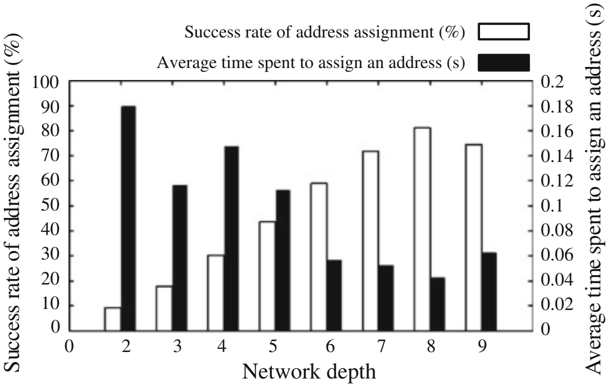


**Fig. 8** Impact of the network depth parameter

Figure 8 reveals the impact of the network depth parameter. As shown there, the success rate of assigning addresses increases from 16.4 to 80 % and the average spent time decreases from 0.17 to 0.09 s when the network depth parameter varies from 2 to 9. This illustrates that in general increasing the network depth has a beneficial effect on the address assignment performance of SBA. We observe that SBA achieves the highest success rate, 81.2 %, and the least time spent to assigning an address, 0.08 s, when the network depth is 8. If the network depth parameter continues to increase, the performance of SBA begins to degrade. This is because the total number of addresses in the 16-bit address space is only 65,535. Thus there is a trade-off between the network depth, $L_m$, and the size of the address space extended by SBA when the values of $C_m$, $R_m$ are fixed. Specifically, if $C_m = 5$, $R_m = 3$ and $L_m = 8$, then $A_m = 16{,}400$ (according to Eq. (11)). Due to $65,535/16{,}400 > 3$, SBA can extend the original address space at least 3 times. However, if $C_m = 5$, $R_m = 3$ and $L_m = 9$, then $A_m = 49{,}205$. Due to $65,535/49,205 < 2$, SBA even cannot extend the original address space on some branches. Therefore, SBA assigns less addresses when $L_m = 9$.

## 6 Conclusion

In this paper, after verifying the existence of the insufficient breadth problem in ZigBee networks, we derived an upper bound of the probability that DAAM exhausts the 16-bit address space, and revealed that there is a spare address space which DAAM does not use in most cases. Then, we propose a segmentation-based on-demand scalable algorithm to address the insufficient breadth problem. Our algorithm allows more nodes to obtain addresses without any extra communication overhead, and it is applicable to address assignment in any ZigBee network consisting of less than 65,535 nodes. Performance analysis and numerical results verify the effectiveness and validity of our proposed algorithm. In addition, we improved the TR protocol to suit the extended addresses. In the future, we will try to find the address-exhausting probability of a branch (it is more meaningful for addressing the IB problem) and address the orphan problem caused by the limitation on both the number of child nodes and the network depth with as less control overhead as possible.

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