Hybrid Address Configuration for Tree-based Wireless Sensor Networks

Yung-Chang Wong, Jui-Tang Wang, Nai-Hsin Chang, Ho-Han Liu, and Chien-Chao Tseng

***Abstract*— This letter proposes a new scheme to alleviate the issue on address acquisition failure in wireless sensor networks (WSNs). The basic idea is to use a hierarchical address structure to make the proposed scheme less susceptible to physical distribution of WSN devices. Simulation results show that the new scheme significantly reduces the failure probability.**

***Index Terms*— address allocation, wireless sensor networks, ZigBee networks.**

I. Introduction

Wireless sensor networks (*WSNs*) is a rapidly growing technology that offers an unprecedented opportunity for a wide spectrum of various applications, including environment and habitat monitoring, healthcare applications, home automation, and traffic control [1], [2]. For each WSN, a coordinator is responsible for starting a new network, when appropriate, setting network parameters, and assigning network addresses to newly associated devices. This paper deals with the problem of address allocation in WSNs.

The ZigBee Alliance [3] specifies Distributed Address Assignment (*DAA*) mechanism for network address allocation. When a new device is willing to join a network, it performs the association process with an existing device in the network. If the existing device has available network addresses, it will assign a free one, in ascending order, to the new device and make it one of its children in the logical address tree. One major advantage of DAA is its tree forwarding capability. For tree forwarding, any device with address a_i can determine the next hop for a packet with destination address a_j simply by comparing the value of a_i with that of a_j, instead of performing a routing table lookup. The weakness of DAA is that a device may fail to acquire an available address from its neighbors. This is called addressing failures. Addressing failures arise either from shortage of available addresses on neighboring devices or from mismatch between setting of topological parameters (described in the next section) and geographical distribution of devices.

Prime Numbering Address Allocation (*PNAA*) [4] serves as a means to avoid the mismatch issue mentioned above. Like DAA, PNAA possesses the tree forwarding capability. Unlike DAA, address trees generated by PNAA are left-skew. This restrains the new devices within the right side region from associating with an existing device in the network.

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This letter aims at designing efficient configuration solutions for moderating the addressing failures further. We propose a compound scheme, named hybrid address assignment (*HAA*), through combining the advantages of both DAA and PNAA. The basic idea is to use the hierarchical address structure to make the proposed scheme less susceptible to physical distribution of WSN devices, while retain the tree forwarding capability.

II. Related Work

This section presents the address allocation mechanisms for WSNs, including DAA and PNAA.

According to ZigBee specification [3], an address tree generated by DAA is hierarchical in the sense that any subtree possesses a block of consecutive addresses. Usually the coordinator itself has a depth d of 0, while its children have a depth of 1. At any depth d of the tree, the addresses are evenly separated by

$$Cskip(d) = \frac{1 + C_m - R_m - C_m \cdot {R_m}^{L_m - d - 1}}{1 - R_m},$$

where topological parameters C_m, L_m, and $R_m \neq 1$ stand for the maximum number of children a parent may have, the maximum depth in the network, and the maximum number of routers a parent may have as children, respectively.

PNAA [4], another address allocation scheme for WSNs, is based on the fact that every positive integer can be written as a product of prime numbers in a unique way. Consider a device with an address a. Let n be the largest prime factor of a. With PNAA, the device can allocate prime numbers $S_p(a) = \{b | b = a \times p\}$, where $p \geq n$ is a prime number, as addresses to new devices attached to it. For example, $S_p(6) = \{6 \times 3, 6 \times 5, 6 \times 7, \ldots\}$, since prime number $n = 3$ is the largest factor of $a = 6$. Normally a root device has an address of 1.

III. Hybrid Address Assignment (HAA) Scheme

This section presents the HAA scheme and the accompanying tree forwarding strategy. With HAA, a device is configured with an address consisting of two fields, separated by a dot. The first field is the i-bit group ID, and the second field, containing the host ID, is j-bit in length. Normally the root device A is configured with the address (1.0), as shown in Figure 1.

When a type-1 device X (a device with address $(a.0)$, $a \neq 0$) receives an association request from a device Y, device X allocates a free address $(b.0)$ to Y, where value b is assigned using PNAA. If this fails, device X then allocates the address $(a.1)$, if free, to Y. Figure 1 shows an example address configuration with $i = 4$, $j = 6$, and parameters $(C_m, L_m, R_m) = (4, 3, 4)$. Take device D with address (4.0)

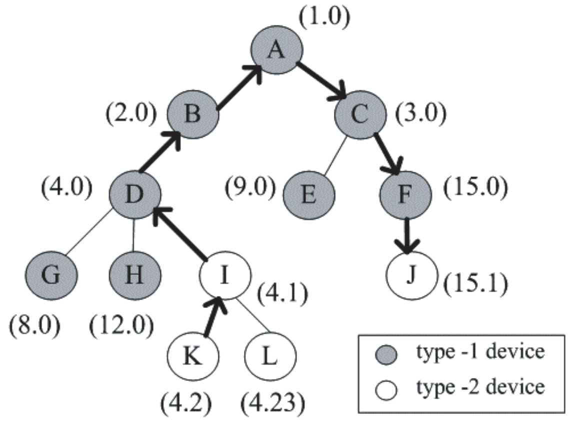

Fig. 1. An example address tree generated by HAA. Arrowed lines represent the packet traveling path.

```
   /* the main loop */
   while not complete do
1      receive a packet pkt destined for address (g.h);
2      if (g.h) = address(X) then
3          relay pkt to upper layer;
4      else if g = group_id(X) then
             /* destined for a tightly connected device */
5          forward pkt to child device with address (g.1);
       else
6          forward pkt according to g by using PNAA;
       end if
   end while
```

Fig. 2. Algorithm 1: packet forwarding for HAA type-1 device X.

```
   /* the main loop */
   while not complete do
1      receive a packet pkt destined for address (g.h);
2      if (g.h) = address(Z) then
3          relay pkt to upper layer;
4      else if g = group_id(Z) and h ≠ 0 then
             /* destined for an inner connected device */
5          forward pkt according to h by using DAA;
       else
6          forward pkt to parent device;
       end if
   end while
```

Fig. 3. Algorithm 2: packet forwarding for HAA type-2 device Z.

as an example. According to PNAA, device D has $8 \in S_p(4)$ and $12 \in S_p(4)$, and assigns addresses (8.0) and (12.0) to devices G and H, respectively. Notably, device D recognizes that $20 \notin S_p(4)$ for integer 20 is out of the 4-bit group ID space. As an alternative, device D assigns address (4.1) to device I.

On the other hand, when a type-2 device Z (a device with address $(c.d)$, $c \neq 0$ and $d \neq 0$) receives an association request from a device Y, device Z allocates a free address $(c.e)$ to Y, where value e is assigned by running DAA. Take device I in Figure 1 as an example. According to DAA, device I calculates the value $Cskip(d) = 21$ with depth $d = 0$ and parameters $(C_m, L_m, R_m) = (4, 3, 4)$, and assigns addresses (4.2) and (4.23) to devices K and L, respectively. As one can see, every host in the sub-tree rooted at device I has a group ID of 4.

Next, let us see how the tree-based forwarding can be achieved in HAA (cf., Figure 2 and Figure 3). For a given address tree, a type-1 device (D in Figure 1) and a type-2 device (L) are said to be tightly connected if one can reach another without crossing any type-1 devices. Accordingly, a type-1 device and a type-2 device are tightly connected if and only if they have the same group ID value. Similarly, two type-2 devices are said to be inner connected if one (K) can reach another (L) without crossing any type-1 devices. It is evident that two type-2 devices are inner connected if and only if they have the same group ID value.

Suppose that, as illustrated in Figure 1, device K wants to send a packet *pkt* to device J, and puts the address (15.1) in the routing header as the destination address of *pkt*. When device I receives *pkt*, it forwards *pkt* to its parent D since *pkt* is destined for a device not inner connected with it (cf., line 6 in Figure 3). When device D (with group ID 4) receives *pkt*, it retrieves the group ID (15) and the host ID (1) contained in the destination address from the routing header of *pkt*. As *pkt* is destined for a type-2 device (J), device D intends to relay *pkt* to device F (with group ID 15), which is tightly connected to the destination device J of *pkt*. Relay of *pkt* is achieved through PNAA tree-based forwarding, according to device group IDs (cf., line 6 in Figure 2): Device D computes the remainder of 4 dividing 15. Since the remainder is not equal to zero, device D selects its parent B as the next hop for *pkt*.

Similarly, devices B, A, and C each independently forwards *pkt* by using Algorithm 1 until *pkt* reaches device F. Upon receipt of *pkt*, device F retrieves the destination group ID (15) from the routing header of *pkt*, and compares the extracted value with its own group ID value (15). Since F is tightly connected with the destination device J, F forwards *pkt* to its child, which happens to be the destination J (cf., lines 4-5 in Figure 2). The packet forwarding completes.

IV. Simulation Results

To verify the effectiveness of the proposed scheme, a 100×100 square units field with N random devices is simulated, where N ranges from 50 to 1000. The communication range of each device is set to 20 units. Moreover, we have the ratio of group ID length to the host ID length be 1:1 and parameters $(C_m, L_m, R_m) = (2, 9, 2)$ in our study.

Figure 4 (a)-(c) shows the failure probability on address acquisition versus the number of devices in the WSN, for address length $L_a = 10, 12$, and 16, respectively. These figures show that the failure probability increases as N increases. For the address length and device numbers considered in Figure 4(a), the HAA scheme encounters fewer addressing failures in all cases. Figures 4(b) and 4(c) show similar results. This phenomenon is explained in two folds. Firstly, it is apparent that for the same number of WSN devices, the address tree generated by HAA is more balanced than that generated by PNAA. As a result, an HAA device is more likely to associate with an existing device in the network than a PNAA device does. Secondly, it is obvious that topological parameters sets a limit on the number of nodes a DAA device can associate with. On the other hand, topological parameters only limit the number of nodes a type-2 HAA device can associate with. Therefore, an HAA device is more likely to associate with an existing device in the network than a DAA device does.

One interesting observation is that when N is larger than 500, increasing L_a can significantly reduce the failure probability for the HAA scheme. This observation justifies the motivation to introduce the hierarchical address structure.

For any device, the average number of address-acquisition requests it received is proportional to the density of devices around it (i.e., the number of devices located within its communication range). The conclusion holds for other communication range values if the device density value remains unchanged.

Furthermore, for a given WSN deployment topology, the address trees of all the three schemes have the same depth. However, HAA requires less address bits than both DAA and PNAA.

V. Summary

This letter addresses the problem of alleviating the address acquisition failures in wireless sensor networks. The basic idea is introducing the hierarchical address structure. This makes the proposed scheme less susceptible to physical distribution of WSN devices, while retains the tree forwarding capability. Simulation results show that the new scheme greatly reduces the failure probability and thus improves the degree of coverage.

Acknowledgment

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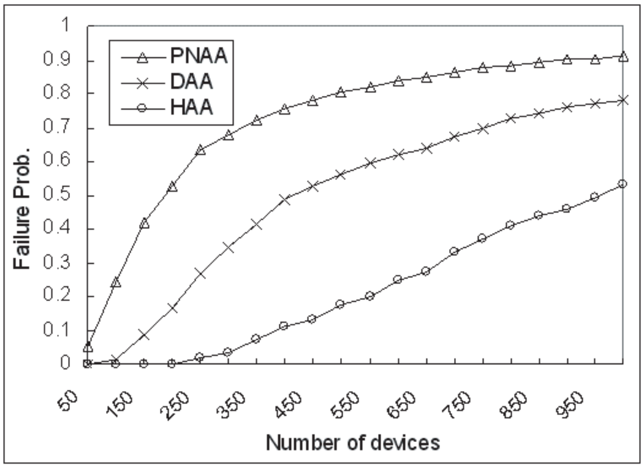
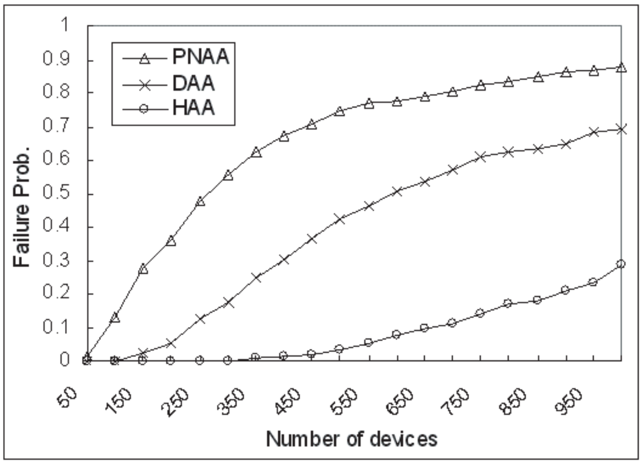
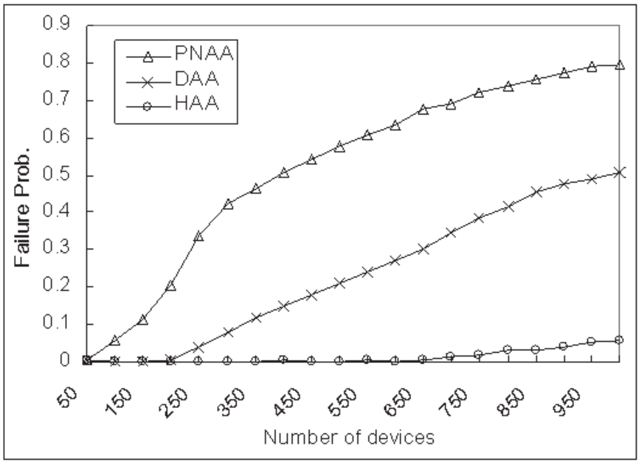


(a)



(b)



(c)

Fig. 4. Failure probability on address acquisition versus number of devices in the WSN. (a) address length $L_a = 10$. (b) $L_a = 12$. (c) $L_a = 16$.