國立交通大學

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碩士論文

混合式具路徑感知識別碼之分配與繞徑機制

A Hybrid Path-aware Identity Assignment and Routing Mechanism

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中華民國九十六年六月

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摘　　要

本篇論文提出一套混合式具路徑感知識別碼（Hybrid Path-aware Identity, HPID）的分配與繞徑機制，本機制將現有之具路徑感知識別碼(Path-aware Identity, PID)的分配機制加以整合，可針對不同網路拓樸，達到有效的識別碼分發。

PID 係指識別碼本身隱含繞徑資訊，其編碼經運算後可以達到路徑選擇的目的。PID 的使用不僅可以免除管理繞送路徑的繁複訊息，同時也可避免建立繞送路徑所產生的延遲。

然而各方所提之 PID 機制皆有某些限制與缺失，僅適用於部分網路環境。因此，本篇論文提出之混合式具路徑感知識別碼（Hybrid Path-aware Identity, HPID）乃針對不同實體分佈之需求，對識別碼加以規劃切割，並結合不同 PID 分配與繞徑機制，達到各機制間的特性整合。因此，HPID 除了具有 PID 的特性及優點外，亦能根據不同實體分佈環境採用適性化的識別碼分配與繞徑機制。

根據模擬結果顯示，本機制可大幅提升各網路實體取得識別碼之成功率，進而縮短識別碼，降低訊息長度，同時減輕繞徑處理時之運算，達到省電之效用。

關鍵詞：具繞徑感知識別碼、混合式識別碼、混合式繞徑、無線感測網路、ZigBee

A Hybrid Path-aware Identity Assignment and Routing Mechanism

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ABSTRACT

In this thesis, we propose a mechanism that can assign Path-aware IDentity (PID) much more efficiently by integrating two or more different PID assignment mechanisms based on the underlying network topologies. PIDs are identities that encode routing information into the values of PIDs so that network entities can deduce routing paths from PIDs simply by performing mathematical operations on PIDs without exchanging routing messages. Therefore, PID assignments not only can eliminate the maintenance overhead of routing tables but also reduce the routing delay.

However, conventional PID mechanisms have their own intrinsic limitations and cannot operate efficiently in various network environments. This thesis proposes a Hybrid Path-aware IDentity (HPID) assignment and routing mechanism that can combine two or more PID mechanisms in accordance of the underlying network topology. Based on the characteristics of the network environment, the HPID mechanism divides an identity into several partitions and adopts a specific PID assignment and routing mechanism for each partition. As a consequence, the HPID mechanism can inherit the salient features and advantages of different PID mechanisms, and thus can adapt to various network environments.

The simulation results show that the HPID mechanism significantly increases the success probability for an entity to acquire a unique identity. Furthermore, it also can shorten the identity length and the computing overhead in routing path selection, and thus reduces the power consumption of each network entity.

Keywords: path-aware ID, hybrid ID, hybrid routing, wireless sensor network, ZigBee

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此外，我要感謝劉合翰同學。本篇論文的成形多虧合翰的協助，尤其第四章的討論亦是因此才有了靈感。我們經過無數次的討論與激盪，終於讓本篇論文更為完整，在這過程中，我深刻體會到合翰於解決事物時的專精以及超強的組織與分析能力。合翰是一個很值得我學習的對象，無論是處事態度、思考能力等等，不但見解獨到精闢，亦有追根究底的精神。能夠和他合作，真是受益良多。

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Chapter 1

Introduction

1.1 Motivation

In the tightly connected world today, entities exchange information with messages. Entities have to recognize each other to transmit data correctly. To recognize an entity, a unique identity is necessary to avoid ambiguity. For example, in a country, people can be recognized with ID cards by the one to one mapping. However, in some situations, duplicate identities are allowed, but the identity should be unique within a local area in general. Identities are also used to manage entities. For instance, students are administrated by student numbers with special compositions. Different segments of the student number represent specific meanings, such as graduated year, department, etc.

Identities have been widely used in networking. For example, in telecom, an operator records profile of a subscriber and administrates a user by IMSI (International Mobile Subscriber Identity). Infrastructures use identities to recognize each other, such as BSID (Base Station Identity) and RSID (Relay Station Identity) in WiMAX. In Internet, MAC address and IP address are used for connection and transmitting data in different network layers. Indeed, an identity acts an important role in entity recognition to achieve communication and management.

Several conventional identity assignment mechanisms have been proposed nowadays and could be categorized as "table-driven" and "path-aware" based on the way to select routing path. Table-driven identity assignment mechanisms assign identity randomly and establish routing table for routing path selection, such as DHCP (Dynamic Host Configuration Protocol) [5]. But these mechanisms have some drawbacks. For instance, DHCP needs a centralized server to allocate an identity (IP address) to an entity (host). Therefore, a joining entity has to do server discovery before acquiring identity. Server discovery is a broadcast message and delays identity acquisition process. Besides, routing table entries proliferate with rapidly growing entities. An entity would spend a lot of time looking up a routing table before transmitting data. Routing table maintenance also needs great control overhead. However, the proliferating table and the additional maintenance overhead are not allowed in some environments. For example, in wireless sensor networks (WSN), both capabilities and power of devices are limited. Extensive routing table would exhaust memory and extra maintenance messages would consume power. Therefore, table-driven identity assignment mechanisms are not permitted under this kind of environment.

In order to solve the problems mentioned above, some experts proposed path-aware mechanisms. Path-aware identity (PID) means an identity has extra routing information within. Instead of using routing table, they establish a tree structure of topology after identity assignment and select routing path directly from the tree. For instance, ZigBee distributed address assignment mechanism [7] assigns address by operation functions based on network settings. Prime DHCP scheme [6] runs a prime numbering address allocation algorithm to compute unique address for address allocation. Furthermore, PID is assigned distributedly, and entity could acquire PID by itself or from its neighbor. However, these PID mechanisms have some problems. For example, the ZigBee mechanism produces operation functions by configuring limitations of the tree, such as maximum number of children a parent may have, maximum depth of the tree, etc. These limitations will restrict flexibility of the topology changing and sometimes they may not be applicable to the network environment practically. In other words, appropriate arranging to tree structure in advance would make identity utilization (1 - failure probability to obtain identity in average) higher. On the contrary, impractical arranging would cause inefficient use of identity space once topology changes over the limitations. On the other hand, the Prime DHCP scheme uses mathematical operation characteristics based on decomposition of prime-factor number, but it has a serious problem that the tree structure is skew. Skew tree structure is not common to entity distribution and will make identity utilization pretty low.

Therefore, we propose a mechanism to solve the disadvantages resulted from the conventional PID mechanisms and improve identity utilization.

1.2 Objective

In this thesis, we propose a Hybrid Path-aware Identity (HPID) mechanism to integrate the conventional PID mechanisms and combine features of them. HPID mechanism could not only take advantages of PID but also make tree structure more balance and flexible. HPID mechanism configures HPID format according to network requirements. We propose a hybrid assignment mechanism to allocate an HPID of each attached entity. Besides, we also provide a hybrid routing mechanism to make routing procedure operated successfully with HPID.

1.3 Synopsis

The remainder of this paper is organized as follows. Chapter 2 briefly introduces the related research efforts. Chapter 3 explains HPID mechanism, including format configuration, assignment and routing mechanisms. Chapter 4 discusses the limitations of our mechanism. Next, evaluation of the conventional PID mechanisms and our mechanism are presented in Chapter 5. At least, we conclude this thesis and introduce future works in chapter 6.

Chapter 2

Related Work

Path-aware identity (PID) means an identity contains routing information by certain mathematical operating, and a routing path can be established from the routing information directly. Therefore, efficient routing is realized without any extensive routing table. Several PID assignment mechanisms have been proposed previously and could be categorized as “structured” and “unstructured” based on the way to produce PID.

2.1 Structured PID Mechanisms

Structured PID assignment mechanism means that it assigns an identity after arranging tree structure. ZigBee distributed address assignment mechanism [20] is a structured mechanism, and we call it the ZigBee mechanism for short in the latter discussion. By the way, classful IP addressing [4] is also a typical example with structured characteristic although it isn’t a PID mechanism.

2.1.1 ZigBee Distributed Address Assignment Mechanism

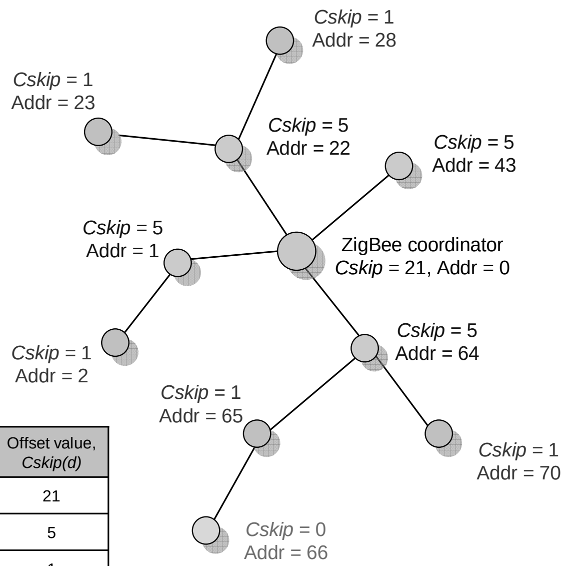
The ZigBee mechanism arranges tree structure by previous network settings, such as the maximum number of children a parent may have (nwkMaxChildren, Cm), the maximum depth in the network (nwkMaxDepth, Lm), and the maximum number of routers a parent may have as children (nwkMaxRouters, Rm). It computes the function *Cskip*(*d*), essentially the size of the address sub-block being distributed by each parent at the depth to its router-capable child devices for a given network depth, *d*, as follows:

$$Cskip(d) = \begin{cases} 1 + Cm \cdot (Lm - d - 1) & \text{, if } Rm = 1 \\ \dfrac{1 + Cm - Rm - Cm \cdot Rm^{Lm-d-1}}{1 - Rm} & \text{, otherwise} \end{cases} \quad (1)$$

Network addresses shall be assigned to end devices in a sequence number with the n^{th} address, A_n, given by the following equation, where $1 \le n \le (Cm\text{-}Rm)$ and A_{parent} represents the address of the parent.

$$A_n = A_{parent} + Cskip(d) \cdot Rm + n \tag{2}$$

This mechanism constructs a tree-structure routing path after allocating identities. Then, an entity could transmit packets according to the computing result of the identity. Figure 2-1 gives an example about how addresses are assigned with the following parameters setting: nwkMaxChildren = 4, nwkMaxRouters = 4, and nwkMaxDepth = 3. In the beginning, a coordinator's identity is 0 and its calculated *Cskip* value is equal to 21. The address sequence that the coordinator can assign is, 1, 1+21, 1+21*2, and so on up to the largest address bounded by the address space or the limited *nwkMaxChildren*. Similarly, an entity having address can calculate its *Cskip* value and allocate numbers in ascending order to the new entities attached to it. However an entity won't have any children if the calculated *Cskip* value is equal to 0.



Depth in the network, *d*	Offset value, *Cskip(d)*
0	21
1	5
2	1
3	0

Figure 2-1 An example of the addresses allocation tree by ZigBee mechanism.

2.1.2 Disadvantages

Structured mechanisms have some problems, such as lack of network flexibility and inefficient use of identity space. Because they all set certain limitations of the network, flexibility of the topology would be reduced. In other words, as the topology changes, entities out of setting ranges could not obtain proper identities. Furthermore, the network setting in advance may not be appropriate to the actual network environment, and then it will waste identities. Namely, in most situations, entities wouldn't distribute in the whole area averagely but appear in some area frequently, so the identities reserved for the other area won't be used.

Inefficient use of identity space is a significant problem. In order to satisfy identities requisition of entities, a manager might try to stretch the length of identities to provide more identities. But stretching the length is impracticable in some network environments. For example, in wireless sensor networks, device capabilities are limited and power saving is undoubtedly a very important issue. Some papers [16] [17] represent that identities with shorter length would diminish computing overhead while routing packets and achieve power saving. On the contrary, stretching identity length would increase overhead and consume more power.

2.2 Unstructured PID Mechanisms

Unstructured PID assignment mechanisms, unlike structured ones, have no beforehand network setting or limitations, so they keep flexibility of topology changing. Prime DHCP scheme [6] is one typical example.

2.2.1 Prime DHCP Scheme

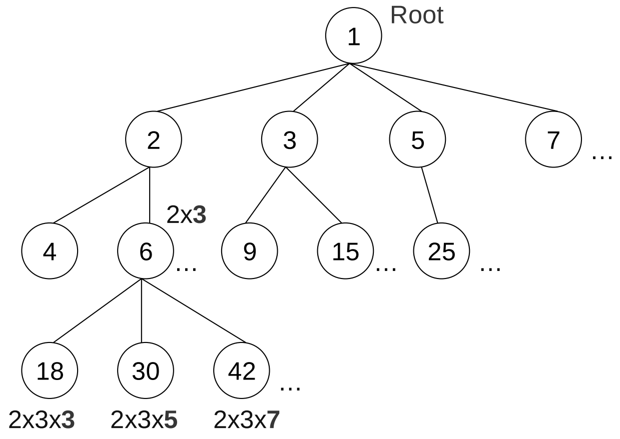


Figure 2-2 An example of the addresses allocation tree by Prime DHCP scheme.

Prime DHCP scheme runs a prime numbering address allocation algorithm to compute unique addresses for address allocation and an entity which is considered as a DHCP proxy could acquire an address by itself or from its neighbor. Figure 2-2 gives an example of addresses a DHCP proxy can assign. The root proxy A has an address of 1 and can allocate prime numbers in ascending order to the new entities attached to it. For a non-root DHCP proxy, it can assign the address equal to its own address multiplied by the unused prime number, starting from the largest prime factor of its own address. Take the entity G with address 6 for example; the largest prime factor of 6 is 3 and the sequence of addresses entity G can assign is, 6*3, 6*5, 6*7, and so on up to the largest address bounded by the address space. Each node needs to maintain its allocation status to record the last assigned address. After the addresses allocation of all entities, a tree structure will be established, and an entity can select the routing path by computing the destination identity.

2.2.2 Disadvantages

Unstructured mechanisms have some drawbacks. For instance, the Prime DHCP scheme would make the tree structure skew and induce inefficient use of identity space more poorly. As mentioned before, using identity space inefficiently will induce another problem that the length of identity should be stretched to content the identity requisition of each entity. But stretching identity length is not permitted in some environments, such as wireless sensor network. Although these mechanisms need no extra settings or limitations of the network, the skew tree structure results in other bad effects.

2.3 Summary

Because both structured and unstructured PID assignment mechanisms have their own problems, we want to propose a mechanism to eliminate or reduce these problems, called Hybrid Path-aware Identity (HPID) mechanism. HPID mechanism not only integrates structured and unstructured mechanisms but also uses identity space efficiently. In the following section we will introduce our mechanism.

Chapter 3

HPID Mechanism

Whereas the drawbacks of the conventional PID assignment mechanisms, we propose a Hybrid Path-aware Identity (HPID) mechanism to eliminate or reduce effects of those problems. HPID mechanism integrates different PID mechanisms to combine their features and provides a hybrid assignment and routing mechanism. According to network characteristics, we could hybridize more than two mechanisms and draw on the strength of each to offset the weakness of the others. Namely, because a structured mechanism has problem about less flexibility of network topology, we could hybridize it with an unstructured mechanism to enhance flexibility. On the other hand, an unstructured mechanism which makes tree structure skew and causes inefficient use of identity space, could be hybridized with a structured one to make the tree structure more balance. Therefore, hybridizing mechanisms could reduce the problems induced by each mechanism and make the use of identity more efficient. Moreover, simulation results indicate that our mechanism provides quite high identity utilization which is better than the other mechanisms.

Next, we will introduce the configuration of HPID format, assignment and routing mechanisms in the following sections.

3.1 HPID Format

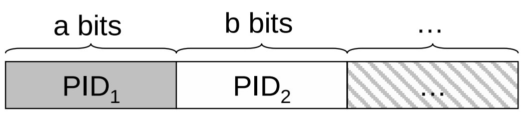


Figure 3-1. An illustration of the HPID format.

To perform HPID mechanism, we have to configure an HPID format in the beginning. First of all, we partition the HPID format into several segments and choose some PID mechanisms for each segment based on network characteristics. Figure 3-1 is an illustration of HPID format, and it represents that there are two or more segments partitioned. Segment 1 is a-bit and uses mechanism PID_1, segment 2 is b-bit and uses mechanism PID_2, etc. In order to explain our mechanism more clearly, we will take a scenario as an example in the following introduction.

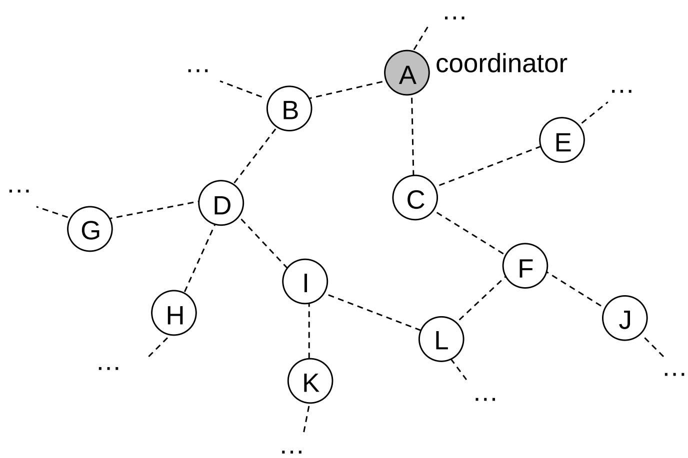


Figure 3-2 Part of the distribution of the sensors.

Consider a scenario that we want to averagely distribute hundreds of sensors in a narrow area to control temperature of soil. Furthermore, each sensor should have a unique identity to recognize each other for sending data. Figure 3-2 illustrates the part of sensor distribution, and node A is a coordinator in the sensor network. Sensor devices have limited capabilities, such as memory and power. Therefore, the conventional table-driven mechanisms which need extensive routing table are not useful in this condition. Conversely, we perform HPID mechanism to allocate identity for a sensor and configure an HPID format as follows.

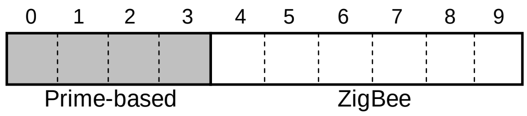


Figure 3-3. Configuration of the HPID format.

As the scenario described, we would configure the HPID format as Figure 3-3, and identity length is 10-bit for hundreds of sensors. Due to the network characteristics we partition the format into two segments. The first segment is 4-bit using the Prime DHCP scheme with sub-identity range from 0 to 15. The second segment is 6-bit using the ZigBee mechanism with sub-identity range from 0 to 63. Because sensors are distributed in a narrow area, the tree structure should be flexible enough to extend the control range. Therefore, the Prime DHCP scheme is chosen for the first segment. Besides, the sub-tree structure should be balance for the average sensor distribution, and therefore we choose the ZigBee mechanism in the second segment. The parameters and *Cskip* values of the ZigBee mechanism are shown as Table 1.

Table 1. Parameters and *Cskip* values at each depth for ZigBee mechanism.

Parameters	
nwkMaxRouter	4
nwkMaxChild	4
nwkMaxDepth	3
Depth, d	***Cskip(d)***
0	21
1	5
2	1
3	0

3.2 HPID Assignment Mechanism

HPID assignment mechanism is a distributed mechanism, and each entity can assign an HPID by operating independently. Later, we will introduce generation and assignment of HPID in two approaches, “forward HPID” and “backward HPID”.

3.2.1 Forward HPID Approach

Figure 3-4 Forward HPID of the 1^{st} type.

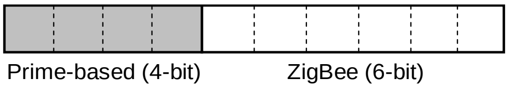


Figure 3-5 Forward HPID of the 2^{nd} type.

Generation and assignment of forward HPID are started form the coordinator, node A in Figure 3-2. In the beginning, node A would produce an identity for itself. While other node attaches to the coordinator, it will process mechanism PID_1 (the Prime DHCP scheme) to generate a forward HPID of the 1^{st} type as form (*a*. 0) shown in Figure 3-4. Among (*a*. 0), the former code, *a*, is 4-bit and produced by the mechanism PID_1, and the latter code is 6-bit with all zeros. Then node A will assign identities to the attached nodes, such as node B and C. While identities of the 1^{st} type have been assigned, node A would generate an only one forward-HPID of the 2^{nd} type as form (*a*. *b*) shown in Figure 3-5. In (*a*. *b*), the former code, *a*, is the same as node A's former code. The latter code, *b*, is a 6-bit non-zero number and produced by mechanism PID_2 (the ZigBee mechanism) initially. Notice that *b* of the 2^{nd} type's identity (*a*. *b*) cannot be zero or identity (*a*. 0) will be duplicated.

While a node has been assigned an identity of the 1^{st} type, it could assign identities to others as node A does. However, if a node is assigned an identity of the 2^{nd} type, it could only generate the 2^{nd} type's identities. The former code of the generated identity is inherited from the node, and the latter code is produced by the mechanism PID_2.

Notice that all of the produced codes should be up bounded by the identity space or within the limited restrictions. Say, the former codes must be within 15 and the latter codes must be within 63.

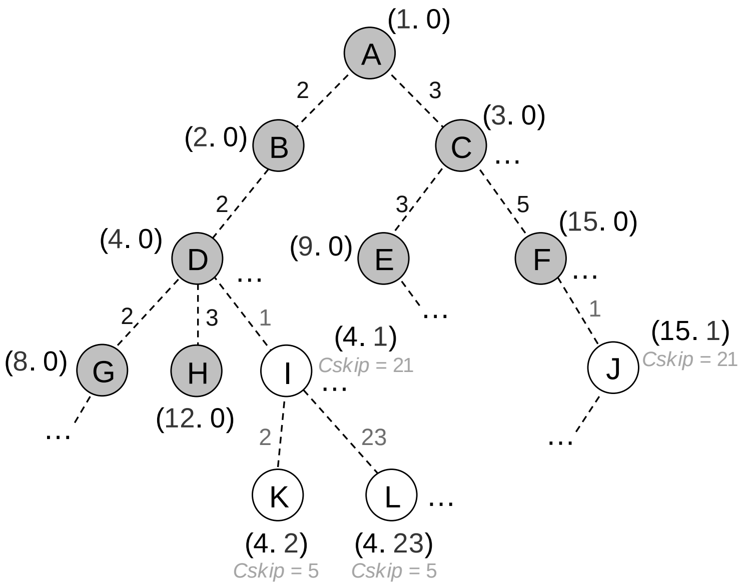


Figure 3-6 The forward-HPIDs allocation tree.

Figure 3-6 illustrates the identities allocation tree. Node A (1. 0) is the coordinator and its former code, 1, is the initial number produced by the Prime DHCP scheme. Identities of node B ~ H are the 1st type as well as node A, and the former codes of each are produced via the Prime DHCP scheme by their parents. Take node F (15. 0) for example, the former code, 15, is produced form node C (3. 0). Because the former code 3*3 has been assigned to node E (9. 0), node C produces a sequential code 3*5 for node F. We call that node A ~ H are nodes on a sub-tree yielded by the Prime DHCP scheme, and node A is the root of the sub-tree.

Node I ~ L have identities of the 2nd type with the invariant former codes to their parents, and the latter codes are produced via the ZigBee mechanism by their parents. Take node I (4. 1) for instance, node D (4. 0) assigns a 2nd type's identity to it because all of the 1st type's identities have been assigned. Therefore, the former code of node I, 4, is inherited from its parent, and the latter code, 1, is the initial number produced by the ZigBee mechanism. The latter codes of node I's children are also produced via the ZigBee mechanism. We call that node I, K, and L are nodes on a sub-tree yielded by the

ZigBee mechanism, and node I is the root of the sub-tree. Notice that the latter code of node I and J cannot be zero, otherwise the identity (4. 0) and (15. 0) would be duplicated.

However, with this approach, a problem and the related phenomenon must be considered.

- **Leak of Identities**

While HPID format has more than two segments, some identities will never be generated, and we call this problem "leak of identities". For example, consider that an HPID format is partitioned into three segments and a root node has an identity as form (*a*. 0. 0) initially. Then the root node will generate identities as form (*a*. *b*. 0) to its children, but *b* must not be zero to avoid duplicate identities. Similarly, a node with identity as form (*a*. *b*. 0) will generate identities as form (*a*. *b*. *c*) with non-zero *c*. Therefore, identities with form (*a*, 0, *c*) will never be generated. This problem appears more significant while the number of partitioned segments increasing.

- **Unnatural Assignment**

Besides, in Figure 3-6, we also observe that node L gets an identity form node I eventually although it can communicate with both node F and I physically. It is because node F has assigned the only one identity to node J. We call this phenomenon that a node can assign only one identity an "**unnatural assignment**" phenomenon. Such phenomenon always occurs in the leaf nodes of a sub-tree yielded by a certain mechanism. For example, node A ~ F are nodes on a sub-tree yielded by the Prime DHCP scheme, and node H and F are leaf nodes.

In order to eliminate the problem and the phenomenon, we propose another approach in the next section.

3.2.2 Backward-HPID Approach with Modification

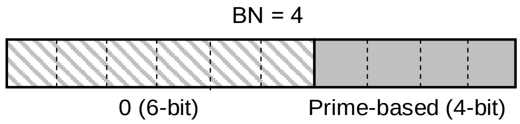


Figure 3-7 Backward-HPID of the 1st type.

The main distinctions of backward and forward HPID approaches are the form of the 1st type's identities and the identities assignment method of the leaf nodes. In Figure 3-7, the 1st type's form of the backward-HPID is (0. *a*) with the all-zero 6-bit former code and the latter code, *a*, which is 4-bit and produced via the mechanism PID_1 (the Prime DHCP scheme). The 2nd type's form is (*a*. *b*) which is the same as the forward HPID. The former code, *a*, is inherited from its parent's code *a*. In other wards, the former code is the same as the latter code or the former code of its parent's identity if its parent has the identity with the form (0. *a*) or (*a*. *b*) respectively. While the latter code, *b*, is 6-bit long and produced via the mechanism PID_2 (the ZigBee mechanism) by its parent.

Notice that the coordinator's identity cannot be zero, otherwise it will cause the duplicate identities. While the code *b* in the form (*a*. *b*) is zero-allowed, and the problem about leak of identities could be solved here.

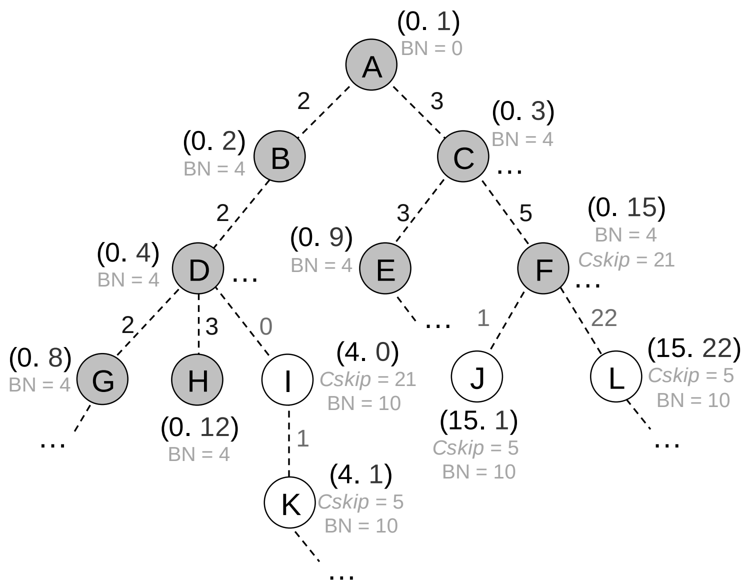


Figure 3-8 The backward-HPIDs allocation tree.

Figure 3-8 illustrates the backward-HPIDs allocation tree which is similar to the forward HPID approach except the 1st type's identities and the modified behaviors of the leaf nodes, such as node F and H. In order to eliminate the unnatural assignment phenomenon, we let the leaf node takes the role as its only one child in the forward HPID approach. Take node F for example, instead of assigning the identity (15. 0) to its child, it takes the role as the node with identity (15. 0) and can assigns more than one identities via the ZigBee mechanism. In other words, the identity (15. 0) is reserved and never be assigned. Therefore, the modified behaviors of the leaf nodes could eliminate the phenomenon of the unnatural assignment phenomenon.

Besides, BN (Bit Number) used for routing procedure represents the length of the meaningful code, including the inherited and produced code. Learning BN's value of each HPID costs no additional messages but just through computing the HPID directly. Say, the 1st type's identity must be less than 16 and the meaningful code is the last 4-bit produced code, so the BN is equal to 4. Similarly, BN of the 2nd type's identity is equal to 10 because of the first 4-bit inherited code and the last 6-bit produced code.

3.3 HPID Routing Mechanism

The HPID routing procedure is performed through computing the HPIDs directly, so it is not necessary to lookup the extensive routing table and fasts the routing latency. Next, we will continue the scenario and introduce the routing mechanism via the backward HPID approach with modification. The routing procedure for the forward HPID approach is trivial and similar to the backward HPID approach, thus we take the backward HPID approach as an example to describe the routing mechanism.

```
(1)  If (RN_BN = D_BN) {
         if (RN_ID = D_ID)
             RN is D;
         else if (RN_Former_ID = D_Former_ID) {
             if (RN_BN = a)
                 run the routing mechanism of PID_1;
             else
                 run the routing mechanism of PID_2;
         } else {
             send to P;
         }
(2)  } else if (RN_BN < D_BN) {
         shift D_ID right b bits;
         if (RN_Latter_ID = D_Shifted_Latter_ID)
             run the routing mechanism of PID_2;
         else
             run the routing mechanism of PID_1;
(3)  } else {
         send to P;
     }
```

- RN - the receiving node
- D - the destination node
- P - the parent node of RN

To perform the routing procedure, the receiving node must to compute the HPIDs of the destination and itself when a node receives packets. The receiving node compares the BNs and conforms the following rules.

(1) If the BN of the receiving node is equal to the destination's, then compare the former code of the HPIDs.

(i) If the former codes are different, then the receiving node sends the packets to its parent directly.

(ii) Otherwise, compare the latter codes of both.

a. If the latter codes are different, then the receiving node performs the routing mechanism corresponding to the latter code. (Namely, if both nodes' HPIDs are the 1st type, then perform the mechanism PID_1. Otherwise, perform the mechanism PID_2.)

b. Otherwise, the receiving node is the destination.

(2) If the BN of the receiving node is less than the destination's, then shift the HPID of the destination right *k* bits to get the shifted HPID, where *k* is equal to

receiving node's BN minus destination's BN. Compare the latter code of the receiving node and the shifted HPID.

(i) If the latter codes are the same, then the receiving node performs the next routing mechanism corresponding to its latter code (the mechanism PID_2).

(ii) Otherwise, the receiving node performs the routing mechanism corresponding to its latter code (the mechanism PID_1).

(3) If the BN of the receiving node is larger than the destination's, then the receiving node sends the packets to its parent directly.

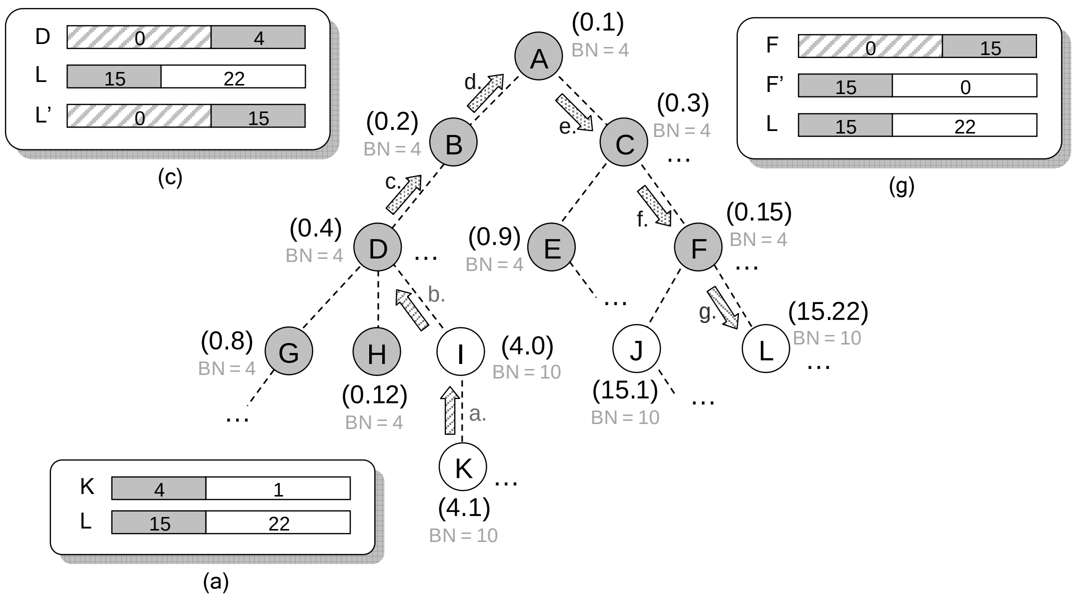


Figure 3-9 The routing procedure via the backward-HPID.

Figure 3-9 illustrates the routing procedure from node K (source) to node L (destination). In (a), node K compares the HPIDs of itself and node L, and sends the packet to its parent (node I) directly because the former codes are different. Node I sends the packet to node D in (b) similar to (a). When node D receives the packet, it shifts the HPID of node L right 6 bits as L' because D's BN is less than L's SN. Node D forwards the packet via the routing mechanism of the Prime DHCP scheme for the different latter codes of itself and L', as well as (d), (e) and (f). Finally node F receives the packet and sends to node L which is the destination via the routing mechanism of the ZigBee mechanism for the dual role as node (15. 0). Finally, the routing procedure is finished.

Chapter 4

Discussions of the HPID Mechanism

We have proposed the HPID assignment mechanism with two approaches, one is forward and the other is backward. Now, we would take the problems induced by each into consideration and process the quantitative analysis.

4.1 Forward Assignment

4.1.1 Leak of Identities

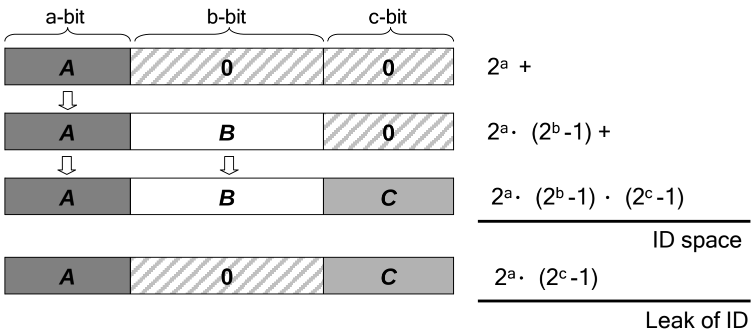


Figure 4-1 Identities leaking of forward assignment on three segments.

The forward HPID assignment is intuitive and simple, but it has a problem about "**leak of identities**" while there are more than two partitions. Figure 4-1 illustrates the situation when the format is partitioned into three segments with a, b and c bits respectively. Here, there are three types of identities, (*A*. 0. 0), (*A*. *B*. 0) and (*A*. *B*. *C*). The 2^{nd} type's identities, (*A*. *B*. 0), inherit the former code of the 1^{st} type's identities, (*A*. 0. 0). In order not to produce the duplicate identities, the middle code *B* should not be zero. Similarly, the latter code *C* of the 3^{rd} type's identities, (*A*. *B*. *C*), would not be zero either. Therefore, the identities as form (*A*. 0. *C*) will never be generated and the amount of those leaking identities is $2^a \cdot (2^c-1)$. However, this problem would be more and more serious as the number of segments increasing.

4.1.2 Quantitative Analysis

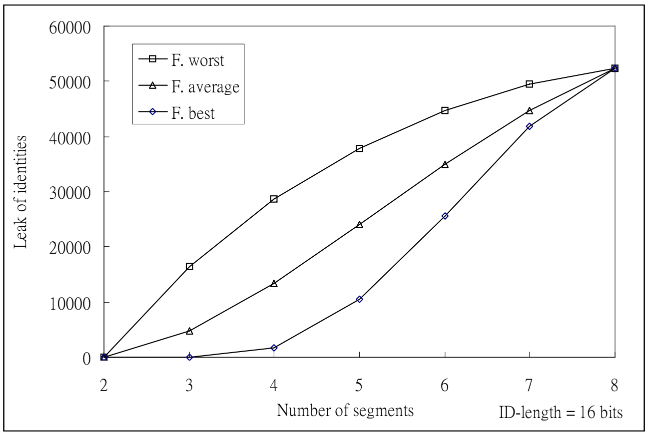


Figure 4-2 Identities leaking of forward assignment.

The following equation calculates the number of leaking identities when there are *k* partitions, where n_i represents the length of segment *i*.

$$2^{n_1} \cdot \sum_{i=1}^{k-2} \left(\prod_{j=2}^{i} \left(2^{n_j} - 1\right) \cdot \left(2^{n_{i+2}+\cdots+n_k} - 1\right) \right),\ k \geq 2 \tag{3}$$

Figure 4-2 shows the effect of identities leaking on the different number of segments for a 16-bit long identity. This figure indicates the worst, average and best cases of identity leaking among the entire HPID formats and assumes that the length of each segment is at least 2-bit long. We observe that no leaking identities there are while the format is partitioned into only two segments, but the number of leaking identities rises obviously as the number of segments increasing. When there are 8 segments, the number of leaking identities is up to 52416 which is almost 80% of the whole identity space. This result also tells us that the forward assignment is not impracticable as the HPID format would be partitioned into many segments.

4.2 Backward Assignment

4.2.1 Leak of Identities

In order to reduce the effect of identities leaking, we propose the HPID assignment with the other direction, called backward HPID assignment. However, the backward assignment can not avoid the leak of identity for all HPID formats. In other words, the backward assignment can prevent the leak of identity just while the length of each segment is the same. But if the length of the first segment is shorter than the others', the problem of identities leaking still occurs. The issue about the longer length of the first segment will be discussed later in the next section. Unlike the forward assignment, the backward assignment would have leaking identities for the format with two segments while the length of the first segment is less than the second one's.

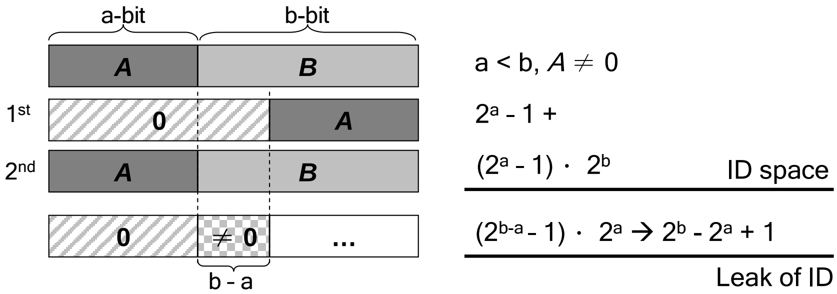


Figure 4-3 Identities leaking of backward assignment on two segments.

An example of identities leaking for two segments is shown as Figure 4-3. In this example, there are two types of identities, (0. *A*) and (*A*. *B*). Since the 1^{st} type's latter code, *A*, cannot be zero, the identity "0" will never be used and cause one leaking identity. Besides, the identities with the first a-bit zero code and next (b-a)-bit non-zero code will never be generated either and the number is 2^b - 2^a. Thus, the total amount of those leaking identities is 1 + 2^b - 2^a.

4.2.2 Duplication of Identities

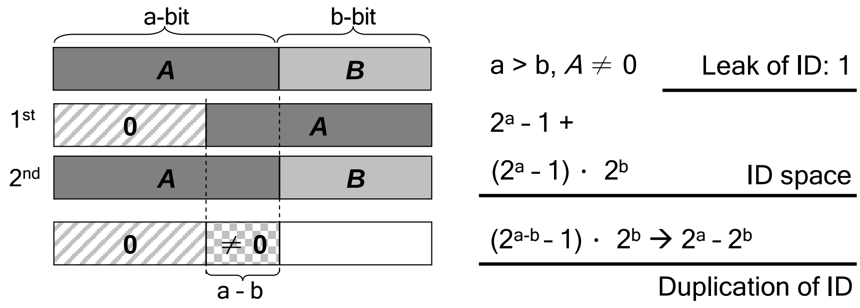


Figure 4-4 Identities duplication of backward assignment on two segments.

However, if the length of the first segment is longer than any other's, the identities duplication will occurs, which is not allowed. An example of identities duplication for two segments is shown as Figure 4-4. Similar to the example of Figure 4-3, there are two types of identities, (0. *A*) and (*A*. *B*). Since the length of the first segment is longer then the second one's, the identities with the first a-bit zero code and next (b-a)-bit non-zero code will be generated twice. But such duplication would not be permitted for the most network environment, so the first segment's length must not exceed the others'.

In order to avoid duplication of identities, we would configure the length of the first segment shortest while executing the backward assignment. Furthermore, we observe that the backward assignment indeed decreases the effect of identities leaking significantly while the number of partitioned segments increases from the mathematical derivation and simulation results.

4.2.3 Quantitative Analysis

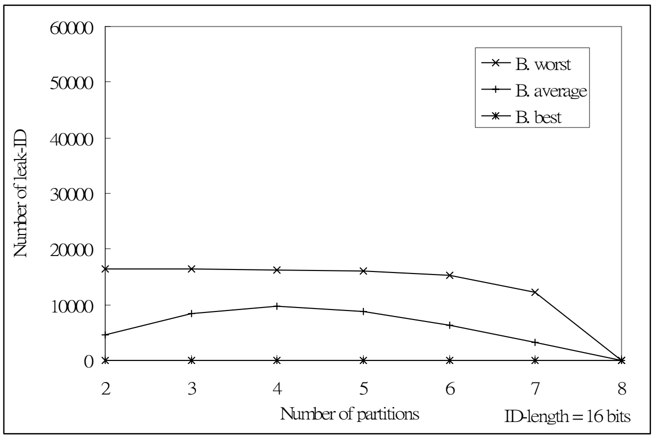


Figure 4-5 Identities leaking of backward assignment.

The following equation calculates the number of leaking identities when there are k partitions, where n_i represents the length of segment i.

$$1+\sum_{i=2}^{k}\left(2^{n_i-n_1}-1\right)\cdot 2^{\sum_{j=1}^{i-1} n_j},\ k\geq 2 \qquad (4)$$

Figure 4-5 shows the effect of identities leaking on the different number of segments for a 16-bit long identity. This figure indicates the worst, average and best cases of identity leaking among the entire HPID formats and assumes the length of each segment is at least 2-bit long. We observe that in the best cases for each number of segments there will be some HPID formats that make the number of leaking identities pretty low. In other aspect, the worst case happens when there are two segments and the number of leaking identities is 16381 which is 30% of the identity space. Comparing to 80% to the forward assignment, the backward assignment really reduces the effect of the problem about leak of identity.

4.3 Summary

If there are just two partitioned segments of the HPID format, the forward assignment is a perfect solution. If the number of segments is three, the performance of both forward and backward assignment is about the same. But if the number of partitioned segments is more than three, the backward assignment would perform better than the other one generally.

However, in the most situations the slight leak of identity is acceptable since the number of identity space usually exceeds the number needed. This is also the reason why we adopt the backward assignment for the simulation and analysis latter. Besides, we still have to notice the problem of identities duplication from the backward assignment and completely avoid the duplication happening.

Chapter 5

Simulation and Analysis

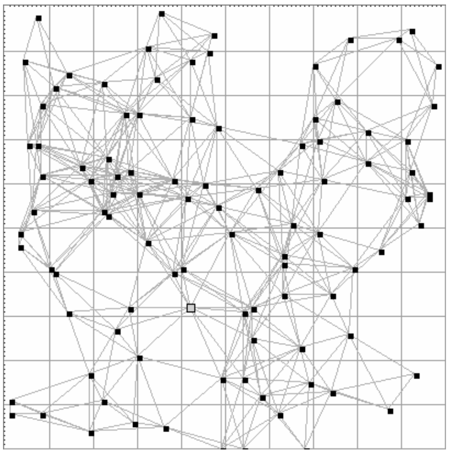


Figure 5-1 An example of network topology for simulation.

The HPID mechanism integrates the different PID mechanisms and combines the features of them. Next, we would give an example for the simulation environment and describe the process of our mechanism. We generate 100 nodes randomly in a 100×100 (square unit) area. The signal range of each node is 20 (unit), thus the node would have 10 neighbors in average. The network topology is shown as Figure 5-1 and the root node is marked as a square.

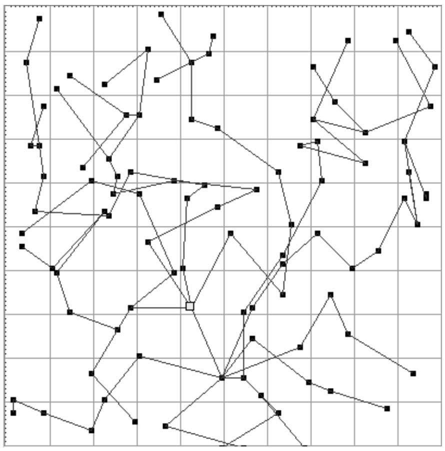


Figure 5-2 The tree structure via the HPID mechanism.

According to the above network topology, we would use 8-bit long identities to identity all the nodes. The HPID format is configured like that the first 4 bits are produced via the Prime DHCP scheme while the last 4 bits are via the ZigBee mechanism (nwkMaxRouters = 2, nwkMaxChildren = 2, nwkMaxDepth = 9). The tree structure of the network is shown as Figure 5-2 after allocating all the identities of nodes via the backward HPID assignment mechanism with modification. All the nodes could get an identity eventually and the average **failure probability** to obtain an identity of each node is 0% which is better than the other two mechanisms. Furthermore, the failure probability also effects the identities utilization of the network directly.

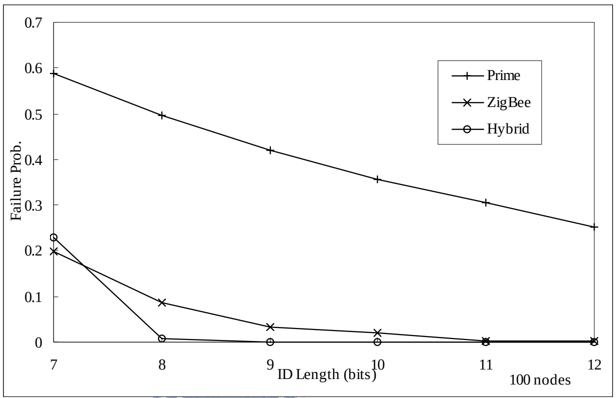


Figure 5-3 The failure probability on different identity lengths.

However, if the failure probability is high on certain length of identity, we may try to increase the length to improve the failure probability. In order to analysis the improvement of the different mechanisms, we simulate the Prime DHCP scheme and the ZigBee mechanism to compare with ours the failure probability of 100 nodes on different identity lengths. In this simulation, the network environment is the same as the above one except the root node which is set in the center of the network area. As the Figure 5-3 shows, the failure probability of each node goes down while the length of identity increasing. When the length is 8-bit long, our mechanism could make all the nodes have their unique identities and the failure probability is almost 0%.

On the contrary, the Prime DHCP scheme does the job awfully and the failure probability is still high while the length is up to 12-bit long. While the ZigBee mechanism needs to increase the length to 11-bit long to make the failure probability drop to 0%. From the results we could observe that for the other two mechanisms the increasing of the length cannot reduce the failure probability efficiently. It also means that these two mechanisms cannot use the identity space efficiently even though raising the identity length. Unfortunately, the increasing of the length is not desirable in some environments and the sensor network is just a critical example. Because to increase the length not only adds the data size but also make the overhead higher while computing the identities to find the routing path. The problems induced by the increased length also consume more power to the sensor devices.

By the way, when the length is 7-bit long, our mechanism is a little worse than the ZigBee mechanism. This is because the length of the partitioned segment is too short and the problem of leak of identities will appear more significant corresponsively.

Next, we will compare our mechanism with the other two related mechanisms to analysis the failure probability to the number of nodes and identity length. The simulation environment is as follows. In a 100×100 (square unit) area, we will generate different number of nodes randomly and set the signal range dynamically to make each node have 10 neighbors in average. The root node is also set in the center of the network area and the length of the identity is configured different number of bits.

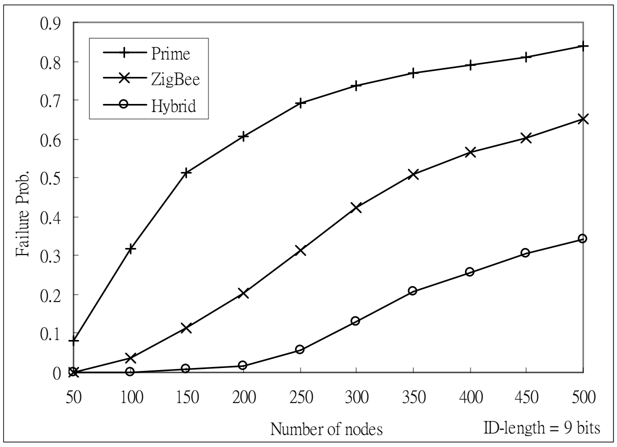


Figure 5-4 Failure probability on various number of nodes (ID length = 9 bits)

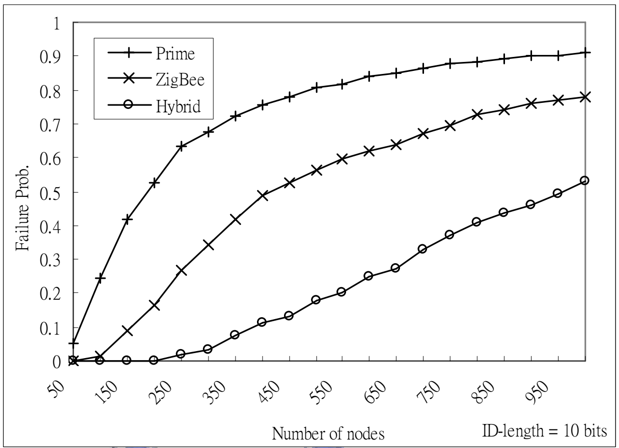


Figure 5-5 Failure probability on various number of nodes (ID length = 10 bits)

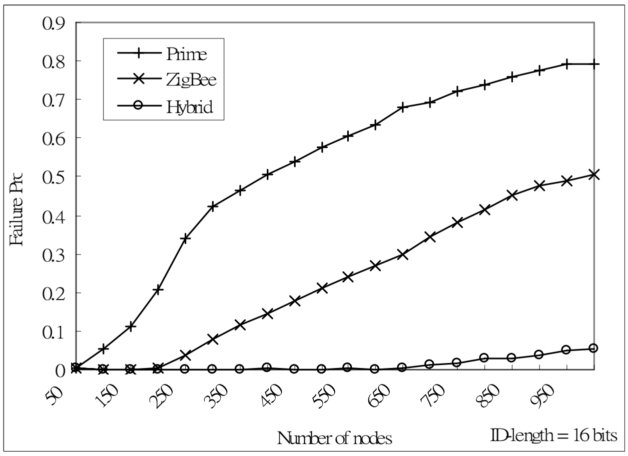


Figure 5-6 Failure probability on various number of nodes (ID length = 16 bits)

Figure 5-4 , Figure 5-5 and Figure 5-6 illustrate the failure probability on the increasing number of nodes in 9-bit , 10-bit and 16-bit long identities respectively. In

Figure 5-4 we observe that the failure probability of the Prime DHCP scheme rises badly, and this curve is induced by the skew tree structure which is not applicable in the most network topologies. Although the curve of ZigBee mechanism seems better than the Prime DHCP scheme, it still increases obviously since the low flexibility of topology induced by the network restrictions. While our mechanism combines the benefits of different mechanisms and does the best job. In a saturated condition where the number of nodes is up to 500, we can also bound the failure probability under 40%. The simulation in Figure 5-5 also tells us the similar results mentioned above. In Figure 5-6, when there are 1000 nodes acquiring for identities among the 65536 identities, the other two mechanisms perform poorly, while our mechanism could still use the identity space efficiently and the failure probability is less than 6%. From the above results, our mechanism indeed decreases the failure probability of each node and also improves the identities utilization.

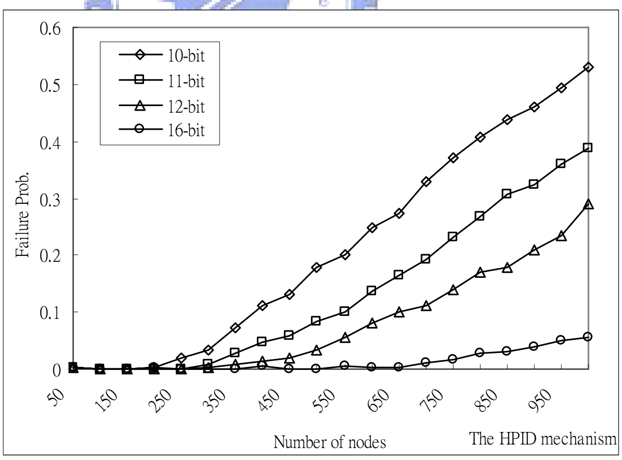


Figure 5-7 Failure probability on various identity lengths for HPID mechanism.

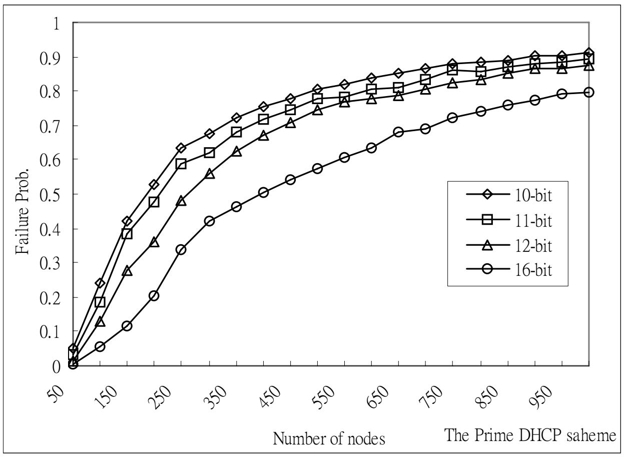


Figure 5-8 Failure probability on various identity lengths for Prime scheme.

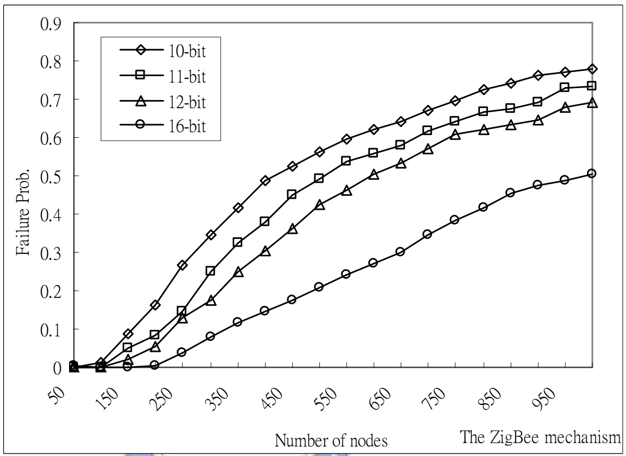


Figure 5-9 Failure probability on various identity lengths for ZigBee mechanism.

Performance of HPID mechanism on the different lengths is shown as Figure 5-7. As the length of identity increasing, the failure probability is improved significantly. But Prime DHCP scheme and ZigBee mechanism could only enhance the failure probability lightly as shown in Figure 5-8 and Figure 5-9. Besides, the performance of out mechanism is also outstanding and these simulation results prove again that out mechanism could use the identity space more efficiently.

Chapter 6

Conclusions and Future Works

We have proposed a hybrid path-aware identity assignment mechanism to integrate the different path-aware identity assignment mechanisms. Our mechanism not only combines the benefits of the others but also improve the identities utilization significantly. Besides, we also propose a hybrid routing mechanism to perform the routing procedure with the HPIDs. Therefore, the routing path could be figured out by computing to the HPIDs directly and no extensive routing table is needed anymore. Our mechanism could not only enhance the performance of routing but also omit the additional messages for table maintenance. Although our hybrid mechanism may increase some computations of devices, the messages omitted could save more power, however. Nowadays the power saving is a very important issue to many network environments. Furthermore, the simulation results also reveal that our mechanism could decrease the failure probability for a node to obtain a unique HPID, which will improve the identities utilization directly. Therefore, we could shorten the length of identities due to the high utilization and the data and computing overhead are both decreased which are also helpful for power saving.

However, there are several types of identities produced by our mechanism according to the number of partitions of the HPID format. We have provided the forward and backward assignment mechanisms and also discussed their features. Besides, the policy to assign the different types' identities can be arranged for the network requirements and features. For example, if a network is composed of the backbone nodes and non-backbone nodes, we can select two PID mechanisms for the HPID format base on the features of the two kinds of nodes respectively. Then the nodes of each kind obtain their identities of the different types. In other words, the HPID assignment policy could be adjusted dynamically through the different requirements. Therefore, each network can have its personalized and applicable HPID assignment mechanism and the identities utilization can be enhanced even more.

There are still many research issues of the proposed mechanism. For example, we would try to figure out the relationships between the HPID format and network features. Provide a method for the selection of PID mechanisms to achieve optimal identities utilization. Besides, we would also try to make our mechanism more robust for fault tolerance and mobility support. If some nodes are broken, the tree structure can heal by itself. If some nodes move, the routing procedure can be operated as usual.

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