# WiBEEM Addressing Scheme Based on NAA Algorithm for High-Speed Mobility of USN Devices

Ho-In Jeon

***Abstract* — In this paper, we proposed an efficient short address allocation mechanism for WiBEEM devices using NAA(Next Address Available) algorithm. The proposed addressing mechanism is based upon the NAA information that is delivered over the beacons every time it is transmitted at the beginning of each superframe. The NAA-based addressing mechanism is not a systematic way of allocating short addresses to newly joining devices and thus tree-routing cannot be supported. However, it has great advantages when U-City core services including U-Parking Lot System or ATIS (Advanced Traveler Information System) services that require high-speed mobility are considered. Moreover, the proposed addressing mechanism can provide significant expandability of the wireless network to various applications and fast device discovery.**

***Index Terms* — IEEE 802.15.4, Mobility of WiBEEM Devices, USN, WiBEEM, ZigBee.**

## I. Introduction

IEEE 802.15.4 Low Rate WPAN [1], [2], [3] is known to be good PHY and MAC (Medium Access Control) specifications for USN (Ubiquitous Sensor Network) devices in the sense that the IEEE 802.15.4 MAC provides not only non-beacon mode but also beacon-enabled wireless network operations in a star topology. When the star topology for the wireless network is under consideration, the beacon-enabled network is especially crucial from the fact that the overall sensor network is synchronized with the beacons transmitted by the PNC (PicoNet Coordinator) and thus every node can get into the deep sleep mode to save the power consumption after CFP (Contention Free Period) terminates, as shown in Fig. 1.

The problem of IEEE 802.15.4, however, is that there is only one beacon allowed to be transmitted at the beginning of each superframe, and thus when a mesh network is implemented on the top of IEEE 802.15.4, the beacon conflicts are guaranteed to occur. In order to avoid these beacon conflicts, all the mesh networks require IEEE 802.15.4 network to be working on the non-beacon mode. This subsequently prevents the mesh network from operating in an Energy Efficient mode.

The ZigBee protocol stack [4], [5] that resides on the top of the IEEE 802.15.4 MAC and PHY layer, as shown in Fig. 2, provides Network Layer protocol, Application Layer, and Security Services. The network layer of ZigBee protocol provides Network Layer Message Broker functionality, Network Management, Routing Management, and Network Security Management. The Network Management functionality in the Network Layer of ZigBee protocol stack takes care of short address allocations, network management, and the growth of the network, while Routing Management functionality handles mandatory

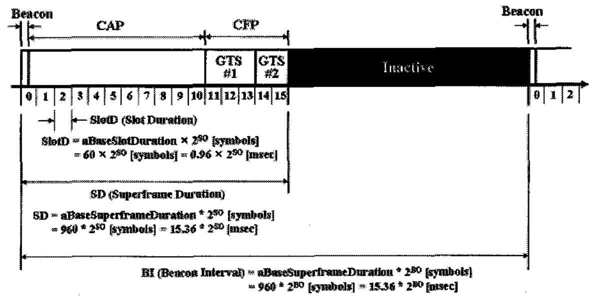


Fig. 1. Superframe structure of IEEE 802.15.4.

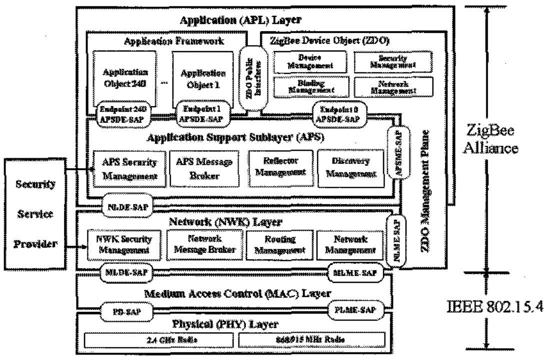


Fig. 2. ZigBee protocol stack residing on the top of IEEE 802.15.4 MAC and PHY.

tree-routing mechanisms as well as optional reactive routing mechanisms of AODV (Ad-hoc On-Demand distance Vector). The Message Broker functionality translates the network layer commands and responds in the way it should.

One of the problems that ZigBee protocol has, however, is that the hierarchical block addressing described in ZigBee Protocol version 1.0 based on $C_{skip}$ address blocks wastes the 16-bit address very quickly. It turns out that when $C_m$, the maximum number of children that a device can associate, is 2, the maximum depth the overall mesh network can have is only 16. When $C_m$ is as large as 7, the depth can reach only 7, which limits the applicability of the ZigBee protocol drastically. This problem can be avoided if we use NAA (Next Address Available) information that is transmitted in the beacon payload of MAC frame format of the new WiBEEM protocol.

In this paper, we propose an efficient way of allocating short addresses in real-time for newly joining WiBEEM devices. The proposed short address allocation scheme based on the NAA algorithm prevents us from wasting the 16-bit address space, by assigning the short address in an incremental manner. The NAA-based addressing also allows the WiBEEM devices to have fast mobility. Section 2 describes the short address allocation mechanism of ZigBee protocol based on hierarchical

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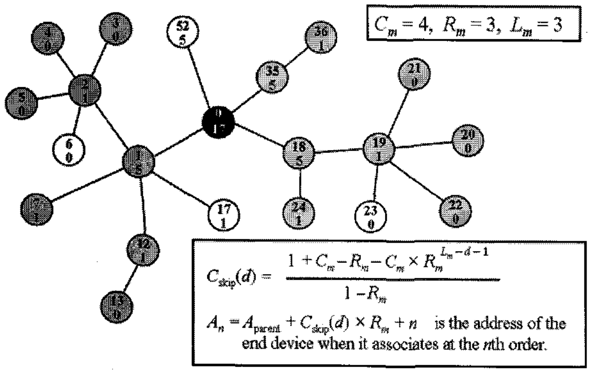


Fig. 3. An example of ZigBee address allocation based on $C_{skip}$ block addressing.

block addressing, and shows an example of such addressing algorithm.

Section 2 explains some characteristics of the hierarchical block addressing of ZigBee protocol. Some limitations of the block addressing mechanism are also introduced. Section 3 describes how the proposed addressing scheme based on the NAA [6], [7], [8] information works. Finally, Section 4 presents the performance comparison between the hierarchical block addressing of ZigBee protocol and the proposed addressing scheme.

## II. Related Work

According to ZigBee protocol, ZC (ZigBee Coordi-nator) or coordinators shall allocate a short address to a newly joining device which just requested to associate with. When allocating short addresses to new devices, the allocation mechanism obeys the rule based on the following parameters: $C_m$, the maximum number of children that ZC or coordinator can allow to be associated; $L_m$, the maximum depth that the mesh network wants to extend; and $R_m$, the maximum number of routers that ZC or coordinators can allow to exist as its children.

Since the parameters $C_m$, $L_m$, and $R_m$ are predetermined before the whole network is deployed, the expandability of the ZigBee network is limited to some extent according to the nature of the parameters. These parameters are set up by the ZC and are stored in the NIB (Network Information Base) registers of all the nodes constituting the network.

When a new device wants to be associated with the ZigBee network, the ZC or coordinators shall allocate a new short address. The best way of allocating a new address is to allocate a block of address spaces to each branch of the tree in such a way that possible address conflicts can be avoided. The mechanism of allocating the address block is to use $C_{skip}$ which can be obtained by applying the following formula:

$$C_{skip}(d) = \frac{1 + C_m - R_m - C_m \times R_m^{\,C_m - d - 1}}{1 - R_m}, \qquad (1)$$

where $C_{skip}(d)$ represents the address block that a coordinator with depth d can allocate for new devices when they request to associate with it. The information about the parameters $C_m$, $L_m$, and $R_m$ is conveyed from its parent. If the value of the $C_{skip}(d)$ is zero, it means that there is no further short address available that can be allocated for the new device and thus the association request of the node to the network is rejected.

The final address of the new device that has requested to associate with the parent at the n-th turn is allocated by its parent device based on the formula:

$$A_n = A_{parent} + C_{skip}(d)\, R_n + n, \qquad (2)$$

where $A_n$ is the address of the new device that the coordinator will assign, $A_{parent}$ is the address of the parent node of the device that will assign a new address, and $C_{skip}(d)$ is the $C_{skip}$ value of the node with depth d that will assign the new address.

An example of ZigBee addressing is shown in Fig. 3, where $C_m = 4$, $L_m = 3$, and $R_m = 3$. The top number shown in the circle of Fig. 3 represents the short address of the node, while the number at the bottom represents the total size of the address block that it can allocate for all the nodes of the specific branch. Note that the nodes in gray circle are routable devices, and the nodes in white circle represent end devices. The End devices do not have routing capability, neither can have a child.

The ZigBee Coordinator(ZC) depicted in Fig. 3 in a black circle has $C_{skip}(0) = 17$. This means that the block of 17 addresses has been allocated for the first branch of node 1, while the same number of address blocks has been allocated to the second child node (node 18), and so the third child node (node 35). The routing-capable device whose address is 1 in Fig. 3 has a block of 5 addresses for all of his child nodes, which are node 2, 3, 4, 5, and 6.

The main advantage of assigning a new short address to a newly joining device using $C_{skip}$ address blocks is that we have a well-defined systematic addressing scheme such that tree-routing can be directly obtained. It is worthwhile to note that a mesh network with tree routing capability does not need to have a large size of memories.

When we consider some special applications in which tremendous number of sensors are collocated in a small area (This is what we call "Dense Mode."), however, such a block addressing wastes the 16-bit address space drastically. Referring to the example shown in Fig. 3, the block of 52 addresses out of 65,536 address spaces have been wasted for addressing only 21 nodes. In other words, the efficiency of the hierarchical block addressing mechanism based on the $C_{skip}$ algorithm is extremely low in terms of the usage of the address space.

The hierarchical block addressing mechanism based on $C_{skip}$ address blocks of ZigBee protocol causes some more problems in addition to the waste of the address space. These include: the limitation of the network expandability; the lack of device mobility; unnecessary and heavy communication traffic when many nodes are located within the RF range of the ZC due to the fact that there are limitations on the maximum number of children.

The limitation of the network expandability can be seen easily by taking a quick look at Fig. 3. Suppose that a new device with its power turned off is located in the RF range of node 4 and the power is turned on later. Presumably, the new node will scan passively and will listen to the beacon of node 4 and will send association request packet to node 4. In this case, there is no more block of addresses that node 4 can allocate to the new device and thus the new device will never be able to join the network, even though node 4 is a coordinator which is allowed to allocate a new address, as shown at the bottom of node 4. The same phenomenon happens to nodes 2, 3, and 5

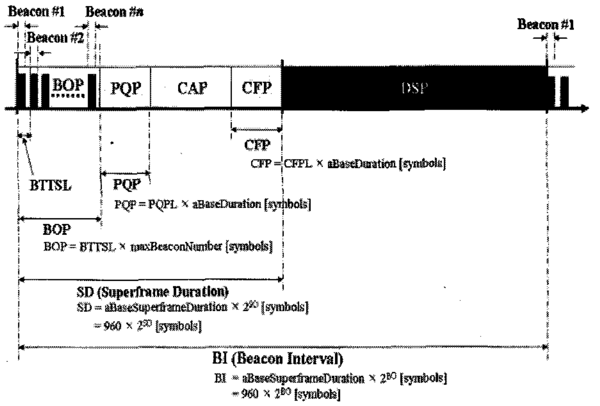


Fig. 4. Superframe structure of WiBEEM protocol.

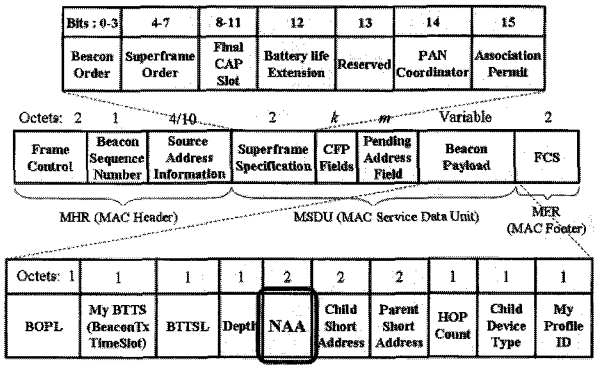


Fig. 5. Beacon frame format of WiBEEM protocol and NAA information contained in the beacon payload.

because they have zero value of $C_{skip}(d)$, which means that there is no more address available to allocate to a new device. This situation stems form the fact that there exists the limitation of the maximum number of children that a coordinator can have and this will limit the applicability of the network drastically.

The lack of device mobility comes from the same argument that has been introduced in the previous paragraph. Suppose that node 6 moves from its original position to the RF range of node 22. In this case, two scenarios can be considered. The first scenario is that node 6 keeps the original address 6 wherever it is located while it keeps the address as the Care of Address. If this happens, the original block addressing of ZigBee protocol cannot be maintained and the tree routing will not be possible. Moreover, node 22 will not be able to allow node 6 to be associated with node 22 due to the limitation of the maximum number of children.

The second scenario is that node 6 gives up his original address and ask node 22 a new address. In this case, the same rejection will occur due to the limitation of the maximum number of children. An additional problem will follow in that the original features of node 6, since it was associated with node 2, may not be kept,and node 2 may keep believing that there is node 6 as its child. Section 3 presents a new addressing mechanism based on the NAA algorithm which can solve these problems that have been addressed in this section. The proposed addressing mechanism is efficient in the sense that there is no waste of 16-bit address space. The short addresses are allocated in real time because the new device can decide his address as soon as he understands the contents of beacon payload. One of the drawbacks of the NAA-based addressing is

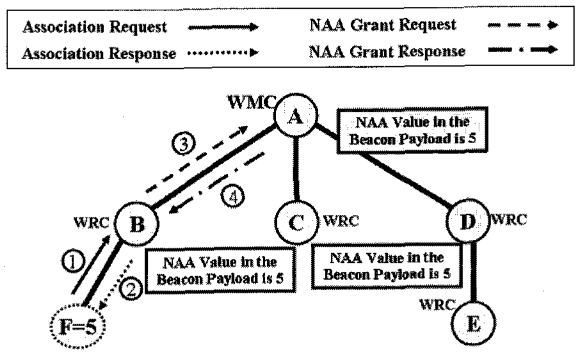


Fig. 6. An example of a Tree Network.

that the tree routing cannot be supported because the addressing is not systematic. The other is that there are possibilities of address conflicts, while the address conflict can be resolved in a reasonable time.

## III. Proposed Scheme

Before we get into the detailed explanation of the NAA algorithm of WiBEEM addressing, we need to introduce the basic concept of WiBEEM protocol which utilizes the BOP (Beacon-Only Period) interval. Figure 4 shows the superframe structure of WiBEEM protocol in which the BOP comes first in the beginning of superframe followed by CAP (Contention Period), CFP (Contention Free Period), and DSP (Deep Sleep Period) in sequence. The interval between the first beacon at the $k^{th}$ cycle and that at the $(k + 1)^{th}$ cycle is called the BI (Beacon Interval). In the BOP of Fig. 4, all the WRCs (WiBEEM Routable Coordinators) transmit their beacons at the time scheduled dynamically in such a way that the transmitted beacon never causes conflicts with those of its neighbor WRCs and its neighbors' neighbor WRCs. This is what we call "Beacon Scheduling" based on Neighbor Tables and Neighbors' Neighbor Tables.

All the beacons transmitted during the BOP contain very important information for the operation and management of the mesh network. Figure 5 shows the Beacon Frame Format which describes each of these information elements. Out of those many fields, the NAA value shown in rounded rectangle in Fig. 5 plays the role of assigning the short address efficiently.

In order to explain the operating principles of the proposed addressing mechanism, we refer to Fig. 6, where node A represents the WMC(WiBEEM Mesh Coordinator), while nodes B, C, D, and E represent WRC(WiBEEM Routable Coordinator). In the Fig. 6, it is assumed that all the devices transmit beacons for the purpose of allowing new devices to join in the network as soon as the new devices understand the beacon of the closest device. To allow this type of beacon-enabled network to operate, we need to schedule the time of the beacons to be transmitted such that there are no beacon conflicts. Readers may refer to other beacon scheduling papers that have been published. We also assume that nodes shown in Fig. 6 joined the network in the alphabetical order.

After active and passive scanning, node A finds that there is no device it can associate with and thus decides to become the WMC of the new network. The protocol says that the first device always has its short address as 0 and the WMC knows the next address (which is generally 1) that it can allocate to the new device. As soon as this initialization process is performed, the WMC sends the NAA information through his beacon which is transmitted every BI (Beacon Interval). The beacon contains the NAA information in the beacon payload, as shown in Fig. 6.

When node B hears the beacon of node A, it knows that the next address that it can have and thus he immediately takes its address as 1. As soon as node B decides to have the short address 1, it sends the Association Request command to WMC. When the WMC receives this Association Request command, it sends back the Association Response command and updates the NAA information and transmits the updated beacon having NAA value as 2.

The whole addressing procedure works this way, and we assume that device E has joined in the network. When node F comes into the network, it also hears the beacon of node B which contains the NAA information as 5 in the beacon payload. According to the similar procedure, node F will have the short address as 5 and this address information is delivered to the WMC. When the WMC receives this information, it updates the NAA information and delivers the new NAA information in the beacon payload.

The rest of the nodes of the network take their short addresses sequentially in this manner. Since the short address are allocated one-by-one assigned by the WMC, there is no waste of 16-bit address space. A good advantage of the NAA-based addressing is that the address space can be reused when the pre-associated devices disassociates and leaves the network. This is achieved by the WMC since it always checks the next address that a new device can have and delivers the information as NAA in the beacon payload every beacon interval.

A possible problem that can happen when operating the network based on NAA is when two devices join in the network simultaneously such that both nodes have the same short address by listening to the NAA information contained in the beacon. When this problem happens, the resolution of the address conflict can be made by using the NAA Grant Request and Response Command. The concern is how long it would be needed to resolve the address conflicts. For the fast mobility of WiBEEM devices, this time needed to resolve the address conflicts should be minimized.

## IV. PERFORMANCE

As mentioned in this paper, the ZigBee network is not efficient in the sense that it wastes the 16-bit address space very quickly. In this section, we explain how quickly the block addressing of ZigBee protocol wastes the 16-bit address space.

Using the $C_{skip}$ formula given in Eq. (1), we can easily compute the address block that each node has to set aside even though it does not actually uses them. Fig. 7 shows the number of addresses that need to be set aside as the function of the depth when $C_m$ and $R_m$ are (2, 2), (3, 2), (4, 2), (3, 3), (4, 3), (5, 3), (4, 4), (5, 4), (6, 4), (5, 5), (6, 5), and (7, 5), respectively. It can be shown from Fig. 7 that when we allow the maximum number of children of the network to be 2, and the maximum number of routable device as 2, the maximum depth of the network was at most 15, while it becomes only 9 when $C_m$ is 5.

When we allow the maximum number of children of the network to be 7 and the maximum number of routable device as 5, the maximum depth of the network was at most 7. The fact that the maximum depth of the ZigBee network is only 16 will limit the applicability of the protocol significantly for

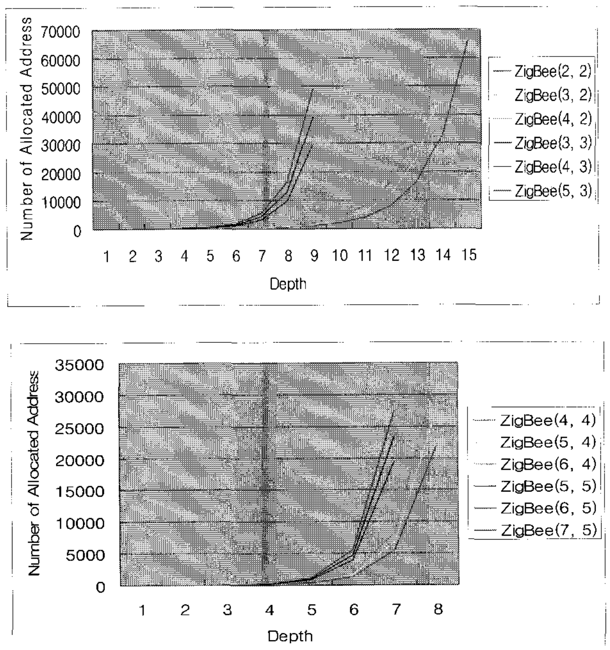


Fig. 7. Waste of 16-bit address space for the case of ZigBee hierarchical block addressing.

the case when the simplest binary tree structure is adopted.

On the other hand, the NAA-based addressing mechanism of WiBEEM protocol does not waste the 16-bit address space at all by utilizing address space reuse functionality. As been mentioned in the previous sections, the WMC completely knows which address has been used and which address has been returned as the address space reuse. In this way, the maximum depth of the WiBEEM protocol can be upto 65,536, even though this will never happen due to the propagation delay over many hops.

## V. CONCLUSIONS

In this paper, we proposed an efficient way of allocating short address in real-time for WiBEEM devices. The proposed short address allocation scheme does not waste the 16-bit address space at all, by assigning the short address in an incremental manner and address space reuse.

The biggest advantage of the proposed addressing mechanism is that it provides an efficient way of allocating 16-bit addresses without wasting the address space. Moreover, it is possible to expand the network without any limitations because there are no limitations on the maximum number of children a WRC device can have. Since each device can have its short address in real-time as soon as it is delivered in the beacon and confirm it with the WMC by broadcasting the new address of the new device delivered in the beacon, the device discovery mechanism is performed automatically. Finally, it provided a good way of mobility support of the nodes, while ZigBee protocol cannot.

These features of the proposed addressing algorithm allow various applications that are being sought in implementing U-City services. The possible U-City services that can be implemented by using the WiBEEM protocol introduced in this paper include: U-Healthcare service, U-Home service, U-ITS service, U-Parking Lot service, U-Gas Station service, U-

Restaurant service, U-Facility Management service, U-Environment Management service, and more.

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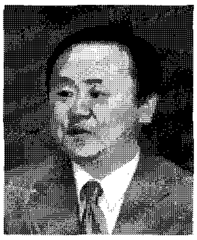

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