Scalable Distributed Address Assignment for Low Rate Wireless Personal Area Network

Shushan Hu
International School of Software, Wuhan University, Wuhan, China
School of Electronic Engineering, Dublin City University, Dublin, Ireland
Email: hushushan@126.com

Cunchen Tang[1], Riji Yu[1], Xiaojun Wang[2]
[1]International School of Software, Wuhan University, Wuhan, China
[2]School of Electronic Engineering, Dublin City University, Dublin, Ireland
Email: cctang@whu.edu.cn, hubeiyrj@gmail.com, xiaojun.wang@dcu.ie

Mei Lei
Information Security Center, Beijing University of Posts and Telecommunication, Beijing, China
National Engineering Laboratory for Disaster Backup and Recovery, Beijing University of Posts and Telecommunications, Beijing, China

***Abstract*—IEEE 802.15.4 protocol provides a low data rate and low energy consumption solution for wireless sensor networks which are the basis of the Internet of Things. However, the variable topology of wireless networks requires high flexibility and robustness to be achieved by network configuration mechanisms. In this paper, a Scalable Distributed Address Assignment Mechanism (SDAAM) is designed, which adopts adaptive approach to handle the variability present in the topology of wireless networks. In the proposed approach, every newly arrived node can be correctly configured regardless of the current network topology so that it can communicate with other nodes within the same network. Another important advantage of SDAAM is its handling of unexpected events which may arise due to migration or departure of nodes in the network. Detailed description about SDAAM is presented and its effectiveness and high flexibility is demonstrated based on the simulation program.**

***Index Terms*—IEEE 802.15.4, wireless network, scalability, Internet of Things**

I. Introduction

The Internet of Things (IoT) [1] is a novel paradigm that integrates modern wireless communications network and control of smart devices. The basic idea of IoT is the pervasive presence of various things or objects around us – such as Radio-Frequency Identification (RFID) tags, sensors, actuators, mobile phones, etc. – which, through unique addressing schemes, are able to interact with each other and communicate with their neighbors to reach a common goal [2]. IEEE 802.15.4 [3-4], characterized with low data rate, short communication range and autonomy, defines the physical layer and the data link layer for the low-rate wireless personal area network (LR-WPAN). With its advantages and huge commercial potential, much research are actively conducting based on IEEE 802.15.4, such as home automation [5-8], smart grid [9], context aware system [10], traffic automation [11] and performance analysis [12-13].

After connecting to the Ethernet, every terminal device applies an Internet Protocol (IP) address, a net-mask, and a default gateway from the network router. Similarly, every node in wireless network should be configured with a unique network address. The dynamic configuration of the Local Area Network (LAN) in the Ethernet is completed by the Dynamic Host Configuration Protocol (DHCP) [14]. Thus, the centralized DHCP server is required to store and manage the configuration data of the network nodes. However, the LR_WPAN devices don't have sufficient memory and compute resource to act as the DHCP server. This indicates the DHCP approach is not suitable for wireless networks. In LR-WPANs, nodes should be able to enter and leave the network at will. The system should configure each node with a network address when it enters the system, and release the address upon its leaving.

this paper proposes a Scalable Distributed Address Assignment Mechanism (SDAAM) aimed at dynamically configuring nodes in LR-WPANs. Based on the difference in device capabilities, wireless nodes are categorized into two types: (1) Full Function Device (FFD); (2) Reduced Function Device (RFD). FFDs can act as a router. In SDAAM, a re-allocation procedure is designed for FFD nodes when they lack sufficient address space to configure their child nodes thereby every newly arrived node can be configured. The proposed approach is also enhanced to handle unexpected events in the network.

Corresponding author: Cunchen Tang, cctang@whu.edu.cn
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The rest of the paper is organized as follows. Section II presents related work and previous attempts to provide address assignment mechanisms for wireless networks. The basic idea and detailed description about the proposed approach are described in Section III. Enhancements for higher flexibility and robustness are explained in Section IV. Section V illustrates the simulation results and performance analyses. Finally, conclusions are given in Section VI.

II. Related Work

A. Distributed Address Assignment Mechanism

In order to calculate the address requirement of the whole wireless network, three integer variables are defined as network parameters in Distributed Address Assignment Mechanism (DAAM).

- C_m: the maximum number of child node a parent node may have.
- R_m: the maximum number of routers a parent node may have.
- L_m: the maximum depth of the network.

The number *Cskip(d)* computed using (1) [15] denotes the size of the sub address block assigned to FFD child nodes by a router at depth *d*.

$$Cskip(d)=\begin{cases}1+C_m(L_m-d-1) & if\ R_m=1\\ \dfrac{1+C_m-R_m-C_m*R_m^{L_m-d-1}}{1-R_m} & Otherwise\end{cases} \quad (1)$$

The network coordinator holding the address of *0x0000* is in charge of the whole network. The address of the r^{th} router node and the e^{th} RFD node are computed by their parent at depth *d* using (2) and (3). In which A_r denotes address of the r^{th} router, A_e is the address of the e^{th} RFD node, and A_p indicates the address of the parent node.

$$A_r = A_p + Cskip(d)\cdot(r-1)+1 \quad (1 \le r \le R_m) \quad (2)$$

$$A_e = A_p + Cskip(d)\cdot R_m + e \quad (1 < e < C_m - R_m) \quad (3)$$

DAAM pre-computes the network address requirement with network parameters. It is simple for every router to allocate an address to the newly arrived node and forward packets to the next-hop nodes without inquiring the routing tables. This eliminates the necessity of routing tables. Some research have been done to improve the forward efficiency [16-17]. However, if the network parameters are not appropriate for the network topology, a newly arrived node may not obtain an address from its parent node whereas there are still sufficient addresses in other FFD nodes. This problem is partly solved by the following solution.

B. Address Borrowing in DAAM

An address borrowing approach for DAAM is presented to improve flexibility of DAAM approach [18]. In this mechanism, even if a router node has exhausted its available addresses, it can still accept a newly arrived node as child node by borrowing one address from another router node which has sufficient addresses. This approach slightly improves the address utilization of DAAM solution. However, it brings additional communication cost during the network construction and more entities need to be stored.

C. Centralized Stateful Address Configuration

Centralized Stateful Address Configuration (CSAC) approach is explained in [19]. Address request messages and response messages are used to accomplish address assignment process. Fig. 1 shows the procedure of CSAC. First, a newly arrived node tries to associate with the network with address request messages sent to one of the adjacent routers called the proxy router. The request messages are forwarded to the network coordinator. On receipt of the request messages, the coordinator allocates appropriate addresses for the newly arrived node by sending response messages to the proxy router. Finally, the proxy router configures the newly arrived node with the response messages.

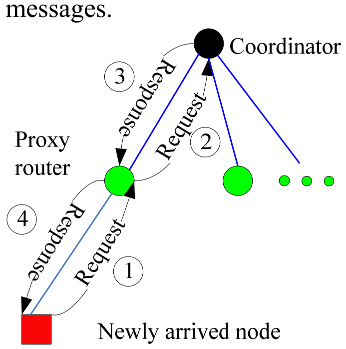

Figure 1. CSAC address allocate procedure

CSAC is the most flexible address assignment mechanism for wireless networks. The address space is directly managed by the network coordinator. Accurate address space is assigned to every newly arrived node thereby this mechanism achieves 100% address utilization. However, because every router node has to store a routing entity for every child node, CSAC causes memory shortage problem, especially for the network coordinator. In addition, due to the numerous inquires in routing table, CSAC is inefficient in forwarding data packets.

III. Proposed Solution

A. Basic Idea

In general, the higher the value of the flexibility threshold, the lower the probability of error, but the greater the latency of the addresses configuration and the greater the demand of compute and memory resources. This is a tradeoff that needs to be balanced while designing a configuration solution. Thus, the core concept of network configuration in LR-WPANs is the balance between the flexibility of the network and the limited hardware resources of wireless devices. The DAAM approach focuses on the limited hardware resources whereas the CSAC approach focuses on the flexibility. A better balance is achieved by the proposed approach. Before the description of the proposed approach, the network parameters are redefined as follows:

- C_o: the initial number of child nodes a parent node may have.
- R_o: the initial number of routers nodes a parent node may have.
- L_o: the initial depth of the network.

And *Cskip(d)* is replaced by $N_o(d)$ computed using (4). $N_o(d)$ satisfies that every router in penultimate $(d=L_o-1)$ can configure C_o RFD nodes, and routers in upper layers $(d<L_o-1)$ has sufficient addresses for $\left\lceil \frac{R_o}{2} \right\rceil$ FFD child nodes and (C_o-R_o) RFD child nodes. In which $\left\lceil \frac{R_o}{2} \right\rceil$ denotes the smallest integer greater than or equal to $\frac{R_o}{2}$.

$$N_o(d)=\begin{cases} 1 & if \quad d=L_o \\ R_o \bullet \left\lceil \frac{R_o}{2} \right\rceil^{L_o-d-1}+\sum_{i=d}^{Lo-1}((C_o-R_o+1)\left\lceil \frac{R_o}{2} \right\rceil^{i-d}) & Otherwise \end{cases} \quad (4)$$

Table I gives an example of $N_o(d)$ computation. N_F is the full number of addresses required by the network (N_F= *Cskip(0)*).

TABLE I.

EXAMPLE OF $N_o(D)$ COMPUTATION

C_o	R_o	L_o	$N_o(0)$	N_F
5	3	3	33	72
10	4	3	65	211
20	5	3	253	621
20	5	4	775	3132

An LR-WPAN example is shown in Fig. 2. The network parameters are: C_o=5, R_o=3, L_o=3. The numbers above the FFD nodes, such as 1, 2, 3, are the serial numbers of FFD nodes which is assigned to every FFD node based on Breadth First Traversal (BFT) mode.

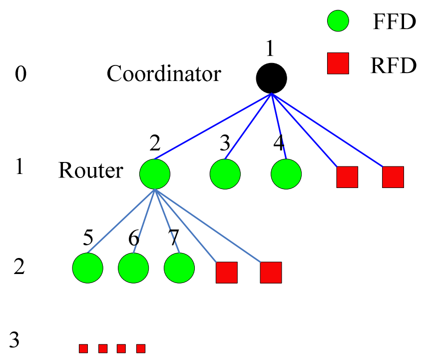

Figure 2. Topology of a LR-WPAN network

Fig. 3 illustrates the structure of the routing tables. In structure of *SDAAM_FFD*, *self_add* is the network address of the node assigned by its parent node. *parent_add* denotes the network address of its parent node. The depth of the node is represented by *node_depth*. *add_space_list* is used to store address blocks allocated to the node. List *child_ffd_list* contains details of address blocks assigned to its FFD child nodes. The structure *CHILD_ADD_NODE* defines nodes of the *child_ffd_list*. *child_add* indicates addresses of child nodes. The start and the end addresses of blocks are recorded in *start_add_list* and *end_add_list* respectively. Structure *SPARE_ADD_NODE* represents nodes structure of the *add_space_list*. *start_add* and *end_add* denote the start and end of spare address blocks. *index_root* and *index_leaf* are used to index addresses allocated for FFD node and RFD node respectively. Insufficiency of addresses at a node can be detected based on them. *free_FFD_list* is the list of free addresses released by departed FFD nodes and *free_FFD_list* keeps that of departed RFD nodes.

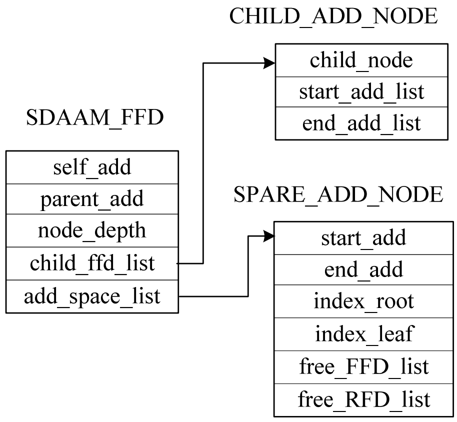

Figure 3. Data structure of routing table

B. Solution Description

Construction of a LR-WPAN starts with the network coordinator initialization. FFD nodes and RFD nodes can join and leave the network at any time when it is complete. The proposed approach contains three basic procedures: 1. network initialization; 2. new node joining; 3. graceful departure of nodes [20].

1) Network initialization

The initialization of LR-WPANs is accomplished by the network coordinator. First, the coordinator completes its initialization as a FFD node with address of *0x0000* and depth of 0. Then a spare address space is initialized with the whole address space from address *0x0000* to address *0xFFFF*. The network is ready for join and depart requests from both FFD nodes and RFD nodes.

2) New node joining

Fig. 4 presents the procedure for new node joining. Several steps are designed to handle it. In step 1, due to hierarchical topology of SDAAM, every FFD node tries to apply address blocks from its parent node. The type of the new device is identified to check whether or not the spare address space is sufficient for the newly arrived node. Free address lists, including *free_FFD_list* and *free_RFD_list*, are firstly checked. If there is a node satisfying the requirement, it is allocated to the newly arrived node from the corresponding list. Otherwise, step 2 is called. In step 2, if the spare address space contains sufficient addresses, appropriate number of addresses are allocated to the newly arrived node. Otherwise, address request messages are sent to the parent node for more addresses. The address re-allocation procedure is described in Section IV. Finally, the joining procedure for the newly arrived node is complete.

3) Graceful departure of nodes

By graceful departure it means that the departing node is being correctly shut down and wishes to relinquish its address prior to shut-down. In such a situation, on the receipt of the departure messages. the parent node of the departing node identifies the type of the departing node to invoke appropriate procedures. If it is a FFD node, its Address blocks are retrieved and inserted into *free_FFD_list* of the parent node. If it is a RFD node, its addresses are retrieved and inserted into *free_RFD_list* of the parent node. For high address allocation efficiency, all nodes of the *free_FFD_list* are arranged. The released address blocks of the departed FFD node are inserted into the *free_FFD_list* at appropriate position. The same as the *free_RFD_list*.

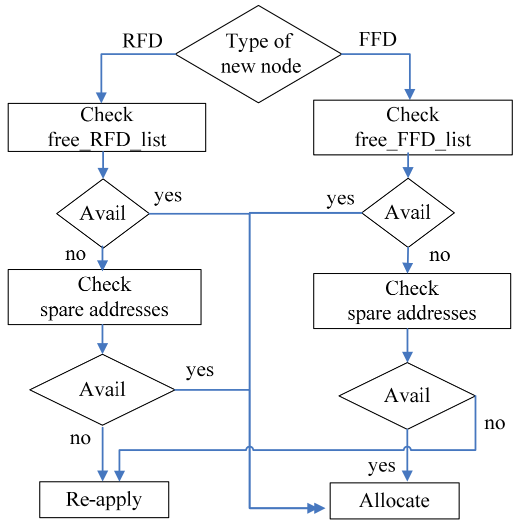

Figure 4. Procedure for new node joining

IV. MAKING THE SOLUTION ROBUST

Section III describes the basic definition about the proposed approach. However, unexpected events may occur in LR-WPANs due to insufficient address space, migration of nodes, etc. These events have the potential to disrupt the network. For example, migration of FFD nodes can lead to the destruction of sub-networks.

This section describes these unexpected events and the enhancements for handling them.

A. Insufficient Address Space at Certain Depth

It may happen in a LR-WPAN that a FFD node (with address *j*) does not have sufficient addresses to configure the newly arrived node *i*. In DAAM, node *i* tries to join other FFD nodes within its communication range. If all of them do not have sufficient address space, it is confirmed that node *i* cannot be associated with the network. This is called as orphan problem in wireless network [20]. This problem is handled by SDAAM via the following procedure.

If node *i* is a FFD node, an address block should be allocated to it. This indicates another address block needs to be re-allocated to node *j* by its parent node. If the parent node of *j* does not have sufficient addresses, it sends requests to its parent node. This process iterates upwards until node *k* which has sufficient addresses. Moreover, if node *j* just requests the exact number of addresses that node *i* needs, there will be more transmission burden and more entities will be inserted into the *add_space_list*. Appropriate number of addresses (calculated using (5)) is re-allocated to handle this issue by node k. Where d_k denotes the depth of node *k* and d_j is the depth of node *j*.

$$2^{d_k-d_j} \cdot N_o(d_j) \quad (5)$$

If node *i* is a RFD node, a single address should be assigned to it. The same as FFD nodes, node *j* should be assigned appropriate number of address (computed using (6)) by its ancestor. In which d_k denotes the depth of node *k* and d_j is the depth of node j. The symbol $\left\lfloor \frac{C_o}{2} \right\rfloor$ indicates the biggest integer less than or equal to $\frac{C_o}{2}$.

$$\left\lfloor \frac{C_o}{2} \right\rfloor \cdot 2^{d_k-d_j-1} \quad (6)$$

B. Migration of Node

It is assumed that node *i* selects node *j* as its parent node and node *i* subsequently moves to another location. As a consequence, node *i* and node *j* are no longer within communication range of each other. Thus, node *i* is isolated from the network and can no longer send and receive packets. Some procedure is therefore required in order for node *i* to inform node *j* about its departure and re-join the network. Heartbeat packets are used to detect migration of nodes and several steps are designed to address this issue.

1. If no heartbeat packets are received within the heartbeat interval, node j marks the situation and waits another confirm time.
2. If still no heartbeat packets after the confirm time, node *j* confirms the disconnection with node *i* and releases address space of node *i*.
3. If no acknowledgment packets are received within waiting cycle, node i re-sends several heartbeat packets.
4. If still no acknowledgment packets after the re-sending process, node *i* confirms disconnection with node *j*. Node *i* sends broadcast packets within its communication range to detect the new optimal parent node.
5. If node *i* is a router, its migration leads to destruction of sub-networks. Re-construction process should be invoked to handle the destruction of sub-networks.

Finally, it is worth noting that the abrupt departure of nodes, which is caused by crashing or abrupt leaving of nodes within the network, is a special case of nodes' migration. So the procedure described above is also feasible for the abrupt departure of nodes. The slight difference is that the departed node *i* no longer tries to be associated with the network.

C. Destruction of Sub-network

The re-construction procedure is designed to handle the destruction of sub-networks. New parent nodes are selected by child nodes of node *i* aimed at re-joining the network. This procedure is illustrated in Fig. 5.

First, if node *i* does not contain FFD child nodes, all RFD child nodes directly scan and re-join the network. Otherwise, FFD child nodes have priority to first send detecting broadcast packets within their communication range. On the receipt of the response packets, signal strengths of the sender are measured and stored. Every FFD child node selects the optimal parent node which has the strongest signal strength. The FFD child node, which owns the best optimal parent node among all FFD child nodes, gets the priority to be associated with the network.

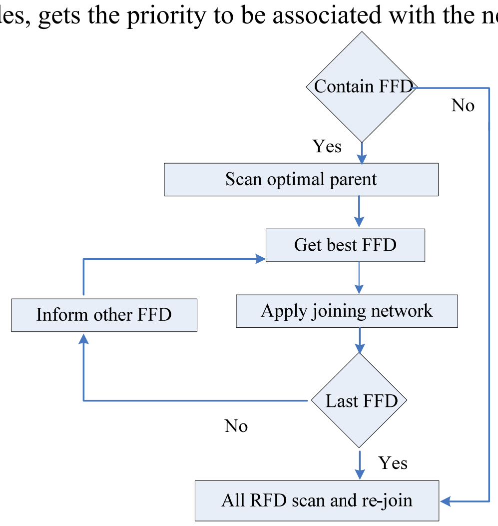

Figure 5. Flow of network reconstruction

After the association, the joined FFD node becomes a potential parent node and informs other nodes about its state. If the joined FFD node is the last isolated FFD node, it informs all RFD child nodes to scan and re-join the network. Otherwise another best FFD child node is selected among the remaining FFD nodes until all FFD child nodes have succeeded in re-joining the network. The re-construction of sub-network is complete after all FFD nodes and RFD nodes have successfully re-joined the network.

V. Discussion and Simulation

A. Review

The proposed approach enables that every newly arrived node can be correctly configured. Moreover, high flexibility and robustness are achieved by it. Unlike DAAM, the proposed approach correctly configures every newly arrived node regardless of the current network topology. It handles the association of newly arrived nodes and graceful departure of nodes. Different from CSAC, structure of the routing table is designed with the target of compressing memory space as much as possible in the proposed approach.

In the proposed approach, both migration of nodes and destruction of sub-networks are correctly handled aimed at improving the robustness of the network. In order to achieve independence from hardware of network devices, the hardware addresses is not adopted by the proposed approach. 16-bit network addresses are used for every device of the network.

B. Simulation

A simulation program was coded with C program language to test the robustness and scalability of the proposed approach. In the simulation program, the number of RFD nodes, configured by a FFD node marked by the serial number, is pre-generated based on the network parameters. The primary focus of the programs is gathering data about address utilization, the ratio of correctly configured nodes to total address space applied by the network, and the robustness of the proposed approach. Simulation for DAAM approach is conducted for comparison with the proposed approach. The simulation program is divided into two parts: (1) simulation with extension; (2) simulation without extension. Simulation without extension is the case in which every router accepts child nodes accurately according to the network parameters. Fluctuation is attached to the number of child nodes in simulation with extension.

1) Simulation setup

The simulation program starts with the network coordinator initialization. Three network parameters are set as follows: $R_o = 5$, $C_o = 20$, $L_o = 3$. As shown in Fig. 6, three data samples are pre-generated. X-axis denotes the serial number of FFD nodes in the network. The number of RFD child nodes configured by every FFD node is shown in y-axis. Data sample 1 indicates that every FFD node configures R_o FFD child nodes. If the depth is less than L_o, (C_o-R_o) RFD nodes are configured by the same node. C_o RFD child nodes are configured at the lowest layer. On the basis of data sample 1, data sample 2 is obtained with triangular wave transformation with amplitude of 5 and the period of 20. The amplitude is changed to 10 for data sample 3.

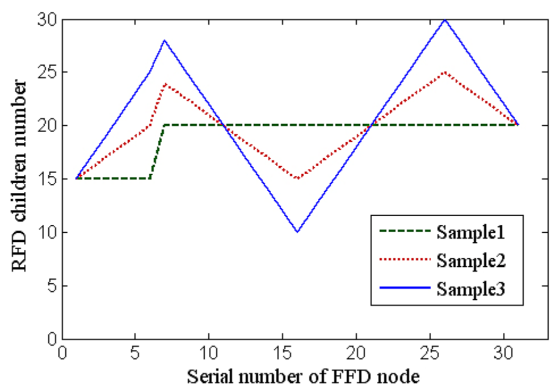

Figure 6. Simulation data samples

2) Simulation without extension

Data sample 1 is used in the simulation without extension. Fig. 7 illustrates simulation results of address utilization. The DAAM approach results are shown as a straight line from 0% to 100%. The results of the proposed approach are different based on different network construction mode, including Breadth First Traversal (BFT) mode and Depth First Traversal (DFT) mode. Both modes are implemented to test the address space utilization ratio of the proposed approach. As compared to DAAM, the results of BFT mode achieve just a little improvement when the number of requests is less than 100 whereas considerable improvement is achieved by DFT building mode.

The average number of messages required for network creation is shown in Fig. 8. Due to the address re-allocation procedure, the proposed approach consumes more messages. So the results of DAAM is lower than the results of SDAAM. The difference between SDAAM and DAAM is negligible, especially the results for BFT mode.

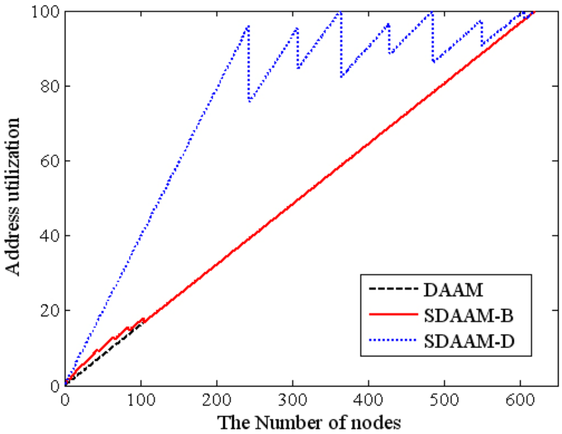

Figure 7. Simulating results on address utilization

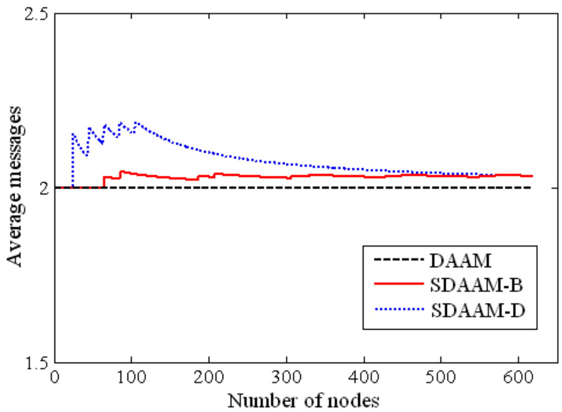

Figure 8. Average messages for network creation

3) Simulation with extension

Data sample 2 and sample 3 are used in simulation with extension in order to test the scalability of the proposed approach,. As shown in Fig. 9, the results of data sample 3 leads to a bigger gap between SDAAM and DAAM compared with data sample 2. The difference in the numbers of nodes correctly configured by DAAM and SDAAM increases with bigger fluctuation in data sample. It is worth to note that SDAAM correctly configures all nodes regardless of the change in data samples.

Finally, the simulation program tests the performance of the proposed approach with great topology extension in the network. Three network parameters are still set as follows: $R_o = 5$, $C_o = 20$, $L_o = 3$. However, the number of routers at depth of 1 is expanded from 5 to 400. Fig. 10 presents the simulation results . The BFT mode provides a normal performance with an almost straight line. But DFT mode performs excellent performance that nearly 100% address utilization is achieved when the number of nodes exceeds 1000.

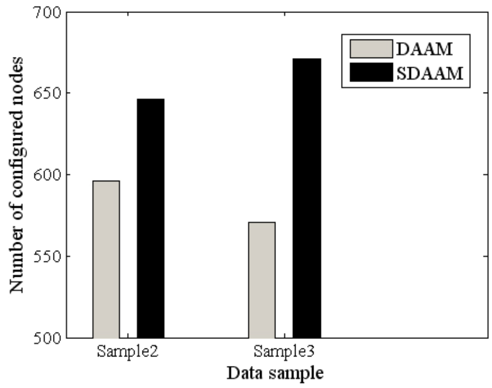

Figure 9. Number of configured nodes in extension simulation

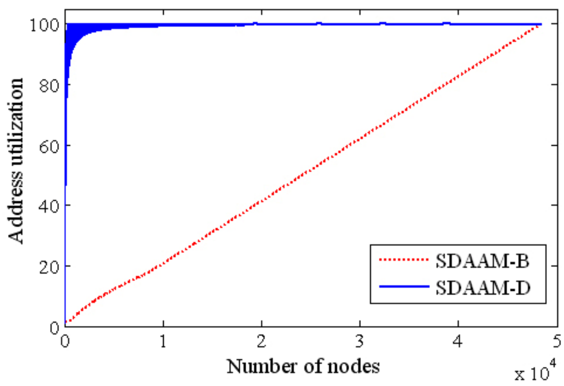

Figure 10. Address utilization of SDAAM with extension

VI. Conclusion

This paper presents a scalable and distributed configuration solution for LR-WPANs. The proposed approach has the following characteristics. First, it ensures that the network is no longer restricted by the network parameters. Next, it overcomes the disadvantage due to the variable wireless network topology and improves the flexibility of the network. Due to limited memory and compute resources of wireless devices, the length of routing tables is reduced as much as possible. Third, unexpected events, caused by insufficient address space at certain depth, migration of nodes and destruction of sub-network, are handled with enhancements of the proposed approach. Simulation results show that the proposed approach can configure all nodes and nearly 90% address utilization is achieved by the experiment network. This indicates that SDAAM performs better flexibility and scalability.

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Shushan Hu was born in China in 1987. He is working on towards PhD degree in the International School of Software at Wuhan University. He received BEng and MEng degree in software engineering both from Wuhan University, P.R.China, in 2009 and 2011 respectively. With the financial assistance from China Scholarship Council (CSC), he continues his research in the School of Electronic Engineering at Dublin City University as a visiting PhD student from Sep.2012 to Sep.2013. His major research interest is smart home based on the Internet of Things, comprised by constructing of home network and intelligent services.

Cunchen Tang received the B.S. degree from the Wuhan University, Wuhan, China, in 1982, and also the M.S. and Ph.D. degrees from the Wuhan University, in 1985 and 1988, respectively. He was selected as the first pilot group to continued his research in Nagoya University, Japan, as a visiting PhD student in 1987.Since 1985, Cunchen Tang was employed as a Lecturer in Wuhan University, where he is now a professor. His research interests include radiolocation, GPS/GIS engineering application, embedded system and application, the Internet of Things, home automation.

Riji Yu received his BS degree in technology of electronics from Hubei University, P.R.China in 1998, and his ME degree in management science from Zhongnan University of Economics and Law, P.R. China in 2006. He is currently a 2nd year PhD student in the International School of software, Wuhan University, P.R.China, and a lectuer in the Animation Department of Hubei University, P.R.China. His research interests include augmented reality, computer vision, and digital culture.

Xiaojun Wang received his BEng in computer and communications from Beijing University of Posts and Telecommunications (BUPT) in 1984 and his MEng in computer applications in 1987, also from BUPT. He was employed as an Assistant Lecturer/Lecturer in BUPT from 1987 to 1989. He received his PhD in Electronic Engineering from Staffordshire University (then Staffordshire Polytechnic) in 1993.

Xiaojun Wang joined Dublin City University (DCU) as an assistant lecturer in the School of Electronic Engineering in 1992, where he is now a senior lecturer. His research interests include energy efficient networking, network security, hardware acceleration for network applications, QoS provisioning and resource optimization in Heterogeneous Networks.