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To cite this article: Xiaolei Zhong et al 2018 IOP Conf. Ser.: Mater. Sci. Eng. 394 032071

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Research on Scalable Zigbee Wireless Sensor Network Expansion Solution

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Abstract. Zigbee technology has a wide range of applications in constructing wireless sensor networks which can increase the number of nodes in the Zigbee network that can be accommodated and expand the wireless sensor network's network size and monitoring range. TI's Z-Stack network protocol stack is used as the carrier for Zigbee technology. On the one hand, the information transfer strategy of the network is improved to increase the capacity of a single network. On the other hand, a multiple Zigbee network cooperative communication scheme is proposed which jointly build a scalable, high-capacity wireless sensor network. Test results on the CC2530 chip show that the actual capacity of a single Zigbee network can be improved and multiple Zigbee networks can be collaborated with each other. It is verified that the scheme not only improves the Zigbee network's overall capacity, but also can flexibly expand, increase or delete Zigbee network size and capacity.

1. Introduction

The Zigbee protocol (Zigbee [1]) has become the most frequently used wireless sensor network architecture due to its low power consumption, low cost, low rate, high capacity, short time-delay, and the ability to support flexible multi-hop self-organizing networks. The Zigbee technology has been able to meet the needs of Smart home, medical monitoring, automatic meter reading and other small and medium-sized network applications, but it still cannot meet the needs of forest monitoring, marine monitoring and other needs of a large number of Node networking. Constrained by many factors such as the node hardware resources, power consumption, and network protocol stack, the Zigbee network size and the number of nodes it can accommodate are far below the theoretical value. The document [2] proposes a two-level abstraction model for large-scale wireless sensor networks. That is, a single gateway wirelessly connects multiple Zigbee subnets, which can expand 16 times of the overall network size. However, the gateway design of the solution is complex and the task with a high load, there will be a large delay after the information is transmitted through the gateway. The gateway will have a high energy consumption and it cannot be downed. The document [3] proposes a tree topology structure that concatenates the Zigbee subnets to build a large-scale network. That is, the information in the subnets is converged wirelessly to the hub node in the network firstly, and all hub nodes exchange information for a tree topology with a wired connection. This solution can increase more...
than 6 times the network size and enhance the overall network's flexibility and stability. However, the sensor hardware resources are generally limited, resulting in few nodes that can be connected in series. In addition, the wired connection between the hub nodes is bound to limit the deployment scope of network nodes. At present, Zigbee's capacity expansion plan is not very large on the one hand, and on the other it is not ideal, so further research is necessary. In order to explore a more effective and feasible Zigbee capacity expansion scheme, this paper researches and improves Z-Stack's information and communication strategies in depth based on the Z-Stack (Zigbee protocol stack), expanding the capacity of a single sub-network and using Zigbee's existing wireless communication methods to connect each Zigbee sub-network without adding new hardware devices, to build a high-efficiency, flexible, scalable large-capacity Zigbee wireless sensor network.

2. Theoretical basis

2.1. Z-Stack and Its Network Structure

Z-Stack is a network protocol stack used by TI to implement the Zigbee technology standard. It has been recognized and promoted by the ZIGBEE Alliance and has become one of the most mainstream and commonly used Zigbee protocol stacks at the present stage. The distributed network constructed by Z-Stack has the characteristics of self-organizing, self-healing, removable, and multi-hop transmission. It can support Zigbee and Zigbee Pro technology, and basically realizes the functional description of the Zigbee standard [4]. The nodes in the Zigbee network have three types of coordinators, routes, and terminals. They support three network topologies: star network, tree network, and mesh network. This paper aims to achieve the Zigbee network expansion goals based on the mesh network structure.

2.2. Reason of Zigbee Network Size Limited

The Zigbee node will be assigned a 16-bit network address in the network. Theoretically, a Zigbee network can accommodate up to $2^{16} = 65536$ nodes [5], but it is actually difficult to achieve this number. Considering that sensor nodes need to be deployed in large numbers, the cost of Zigbee modules is generally relatively low. Therefore, the hardware resources of Zigbee modules are very limited. Random Access Memory (RAM) is required for system operation, data processing, and information exchange. Therefore, the area for storing the routing table is very tight, resulting in a very limited network size that can be recorded. On the other hand, the Z-Stack protocol stack limits the NWK_MAX_ROUTERS parameter to 6 and the NWK_MAX_DEVICE_LIST parameter to 20, that is, up to 20 child nodes can be mounted under a node, and at most only 6 are allowed as routing nodes. Based on this, a single network is calculated. There are only a few hundred nodes that can be accommodated [8]. The limited hardware resources and the inefficient use of resources in the protocol stack and the limitations of the protocol stack itself have led to the limited size of the Zigbee network.

3. Zigbee network expansion design

3.1. Zigbee Single Network Expansion

Expanding Zigbee's single-network capacity starts with improving the efficiency of RAM usage, increasing the number of nodes that nodes can mount, and increasing the network depth. The specific implementation is shown in Figure 1. Adjust the STACK_PROFILE_ID to ZIGBEEPRO_PROFILE to increase the number of child nodes that can be mounted on the node. Increase the protocol stack MAX_NODE_DEPTH to improve the total number of network layers. This value indicates how many subnodes the network is allowed to mount. For a route with a terminal in the child node, execute sonAssoListClearEntry () and sonNeighborClearEntry () to delete the related routing information of the terminal in its associated table and neighbor table to release the RAM space. If other nodes need to send information to the terminal node, the network address of the terminal parent node needs to be
looked up in the coordinator's endAddrTab table and that is sent to the parent node. After the terminal wakes up, the information is retrieved from the parent node.

Modify STACK_PROFILE_ID to ZIGBEEPRO_PROFILE
Expand MAX_NODEDEPTH

Routing node

Send directly

Other nodes

Whether the target node is a terminal

Execute NLME_JoinRequest()
Request to join the network

Enable AODV route discovery algorithm to establish transfer path routing table

Child node

ZDO_JoinConfirmCB()

Is it a terminal?

Y

Send to parent node

Execute app_query_addr()
Query target parent node URL

Send the URL of the terminal child node to the coordinator

Execute NLME_UpdateNV()
Save the endAddrTab table to the NV area

N

Executes sonAssoListClearEntry() and sonNeighborClearEntry()
Delete routing information of terminal sub-nodes

Execute osal_mem_free()
Free up RAM space to accommodate routing entries and child nodes for larger networks

Figure 1. Expanding the capacity of child nodes

3.2. Multi-Zigbee Subsystem Collaboration and Implementation

Zigbee allows multiple personal area networks (PANs) to co-exist in a single area. This paper explores the connectivity of multiple PANs on the basis of this, so that each PAN can perform its own tasks independently and cooperate with each other. The core idea is: First, the network parameters of each PAN are strictly controlled so as to prevent the information in the network and the nodes from leaking to other PANs, causing mutual interference among PANs. Second, wireless communications are used to build communications between two adjacent PANs. Finally, an information transfer strategy between multiple PANs is established, and the information is delivered to a specified node in the target PAN network by means of multi-hops.

a. Each PAN must use separate, preset, known network parameters such as PAN network identifiers, channels, and frequency hopping, and do not use fuzzy network management rules.

b. Because of the Z-Stack protocol stack, the network layer and the bottom layer are not open source, the use of the network layer to communicate between PANs cannot be realized directly, and the network parameters used by each PAN are not the same, and the direct information transmission between the PANs is also full of challenges. Although each PAN network parameter is different, their
protocols, data formats, and communication processes are consistent. Through the research and improvement of the Z-Stack protocol stack, the data can be encapsulated into the data format of neighboring PANs, the transmission parameters can be adjusted, and the data transmission process can be improved. Finally, the data packets are delivered to the specified nodes in neighboring PANs.

The specific implementation method is shown in Figure 2. After the initialization of the node ZA in the A network is completed, the user task port is registered to the Application Sub layer Support (APS), and then ZDOInitDevice() is started to start the network. For data packets sent to the neighbor PAN, it first switches to the target channel, and then calls AF_Data Request() to encapsulate the network parameters and data into packets in the neighbor PAN format and send them. After the transmission is completed, the channel is switched back to the original channel. The node ZB in the B network receives the data packet from the neighbor PAN and parses it according to the common data parsing process. According to the DstEndPoint value in the data packet, it can determine whether the packet is from the neighbor PAN or the internal network, and then calls a corresponding processing function.

![Figure 2. Communication process between neighbor PANs](image)

c. In order to highlight the key point, a PAN is regarded as a whole at this time. A mesh network topology is also established between multiple PANs through wireless communication. The communication path between any two PANs is based on the path quality and distance. The Zigbee Extend Ad hoc On-demand Distance Vector Routing (ZE-AODV) algorithm is designed to establish an optimal routing path between PANs and relay information through multiple hops and relays. The specific algorithm is described as follows:

① After coordinator establishment in 1PAN is completed, an inter-PAN neighbor discovery message is broadcast to find neighboring neighbor PANs, and a PAN inter-neighbor table panNeighborTable is established;

② In the PAN, the coordinator broadcasts an inter-PAN route request packet to the coordinators in all neighboring PANs. The coordinator in the neighbor PAN continues to broadcast the packet after receiving the packet. Each time the packet passes through a coordinator in a PAN, The value of the link quality is added to the message. After all the paths reach the coordinator in the destination PAN network, the destination PAN coordinator replies with a message to the initiator PAN coordinator according to the path with the lowest link consumption in the message, and the coordinator in the PAN along the path will take the path Recorded in its own PAN routing table panRouteTable, as shown in Figure 3;
The other nodes in the PAN send information to the nodes in other PANs. The information needs to be sent to its own coordinator, and the coordinator is responsible for forwarding. The own coordinator forwards directly if there is a transfer path of the target PAN. If not, the previous inter-PAN route discovery algorithm is executed, and the path is determined and forwarded to the specified node in the target PAN.

To add new PAN networks for expansion, just add the new PAN to the entire network in accordance with (a) (b) (c) above.

4. Experimental results and analysis

The Zigbee protocol stack tested in the system is Z-Stack-2.5.1a, the node hardware device uses the CC2530 chip, and the integrated development software is the IAR EW8051 V8.1.

4.1. Single PAN Expansion

The focus of the single PAN expansion strategy is to improve the edge routes for which the terminal subnodes are attached. Therefore, a PAN is set up in the same area. The topology structure is shown in Figure 4. After the entire PAN is set up, the test route ZR1 mounts three terminal subnodes and is connected to the computer through the debug line to observe the operating status of the protocol stack. FIG.5 shows the association table of the route ZR1 AssociatedDevList [] and the neighbor table neighbor Table [] in the IAR software debugging mode on the computer.

![Figure 3. Path discovery algorithm between PANs](image)

![Figure 4. PAN topology](image)
AssociatedDevList [] records node information directly related to itself, shortAddr=0 and node Relation=0 of AssociatedDevList [0], indicating that the node network address recorded by AssociatedDevList [0] is 0x0, which is the parent node of this node. In the topology of FIG. 4, the parent node of the test route ZR1 is the ZC coordinator, and the network address is exactly 0x0. Neighbor Table [] records neighbor node information within its own single-hop range. Neighbor Table [0] = 33564 (0x831C) of Neighbor Address is the network address of its neighbor route ZR2, panId=65521 (0xFFF1), which is exactly the same as the PANID of the network. The Location column in Figure 6 is the address of each element of the array. The first address of AssociatedDevList [1] minus the first address of AssociatedDevList [0] is the length of memory occupied by an array element LENasso, ie LENasso=0x0B37-0x0B25=0x12 (Byte). In the same way, the single element in the neighbor Table [] occupies the memory length LENngb=0x17 (Byte). To improve the association table and neighbor table, it needs the space of AssociatedDevList [NWK_MAX_DEVICES] and neighbor Table [MAX_NEIGHBOR_ENTRIES], NWK_MAX_DEVICES=21, MAX_NEIGHBOR_ENTRIES=16. After the improvement, it only needs to occupy the space of AssociatedDevList [7] and neighbor Table [6] to save space: (NWK_MAX_DEVICES-7) *LENasso+ (MAX_NEIGHBOR_ENTRIES-6) *LENgnb=482 (Byte), saving 6% space compared to CC2530 8K RAM Can accommodate larger routing tables and more nodes.

4.2. Multi-PAN Interoperability

The communication between PANs is performed in the form of multi-hops through the relays of multiple PANs. At this time, PAN is still regarded as a whole network element, and a multi-PAN coexistence network structure as shown in FIG. 6 is constructed. PAN communicates wirelessly and the coordinator ZC4 is connected to the computer through a debug line. One in each PAN coordinator, route, and terminal represents the network.

After the network is started, the coordinator ZC1 of PAN1 sends data to the coordinator ZC4 of PAN4 for the first time, and the broadcast path search is started. PAN1’s search message will reach PAN4's ZC4 through multiple paths. There are a total of 4 paths from PAN1 to PAN4:

Path0: PAN1-PAN3-PAN4;
Path1: PAN1-PAN2-PAN4;
Path2: PAN1-PAN3-PAN2-PAN4;
Path3: PAN1-PAN2-PAN3-PAN4;
ZC Coordinator

Wireless Link

Figure 6. Multi-PAN communication network architecture

Figure 7. Node status in target PAN
We use IAR software to view the operating status of node ZC4 on the computer, as shown in Figure 7. PanRtDiscTable [] is an array of inter-PAN path discovery caches. An element represents the last-hop PAN in a path. The previous PanIDs of panRtDiscTable [0] and panRtDiscTable [3] are 65523 (0xFFF3), indicating that the one-hop PAN is PAN3 on these two paths and the corresponding paths Path0 and Path3. Similarly, panRtDiscTable [1] and panRtDiscTable [2] correspond to paths Path1 and Path2. Then, ZC4 in target PAN4 will return an acknowledgment message to ZC1 in the source PAN according to the path with the best link quality in panRtDiscTable []. The route along the path confirms whether it is on the path according to the message, and establishes the corresponding forwarding table panRouteTable[]. The ZC1 running state is shown in FIG. 8, and it can be seen that dstPanID=0xFFF4 and nextHopPanID=0xFFF3 in the created panRouteTable [0], and the panRouteTable [] of ZC3 in PAN3 also has the corresponding entry of the path, the dstPanID of the entry is 0xFFF4, nextHopPanID. =0xFFF4. At this point, the establishment of an optimal path for forwarding the information between the PANs is completed, and the communication between the PANs is transmitted according to the forwarding table panRouteTable [].

![Figure 8. Node Status in the Source PAN](image)

The single-network expansion scheme saves 6% of the RAM, and the deletion of the entries of the terminal sub-nodes also avoids the frequent disconnection of the child nodes and the associated table overflow in the parent node RAM. In addition, Zigbee allows 100 PANs to co-exist in the area and integrates two expansion strategies. The overall network capacity can be expanded by at least a few hundred times. Such a network formed by multiple PANs not only retains Zigbee's low-power, low-cost, self-organizing features, but also accommodates a large number of nodes, and can also flexibly expand or delete PANs at any time.

5. Conclusion
The test results of the CC2530 chip show that the available space of the node RAM is increased. At the same time, the node running status in the multi-Zigbee network indicates that the data packet not only succeeds in achieving cross-network transmission, but also transfers according to a preset optimal path. It is confirmed that the single-network capacity expansion and multi-network cooperative communications jointly improved the feasibility of the overall network capacity and scale. Compared with the current expansion plan, the system does not need to upgrade the hardware nor increase the hardware. In theory, it can expand the network capacity by at least a few hundred times. It provides an efficient, low-cost, extensible solution for Zigbee high-capacity networking. Currently, due to limited resources, it is impossible to actually deploy thousands of node tests. In the future, we will seek cooperation in various aspects to further verify and explore the improvement of the actual performance of this solution under thousands of Zigbee nodes.
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