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IPv6-Based Architecture of Community Medical Internet of Things

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ABSTRACT The effective integration of Community Medical Internet of Things (CMIoT) and the core technology IPv6 about the next generation of Internet will create a new pattern for the medical field. However, as a heterogeneous network system, the interconnection of different CMIoT components is the primary problem, which needs to be solved. Traditional protocol conversion gateway in the Internet of Things only implements the packet format conversion. When the network environment changes, it is difficult to effectively implement the data path. We propose a CMIoT architecture with the assist of the communication auxiliary gateway, and design the simplified protocol message format under the premise of satisfying the functional requirements. At the same time, the CMIoT architecture model is built based on the Ptolemy II modeling environment and implemented in a community, and it is proved that the interconnection between the IPv6 network and the physical network can be realized more effectively.

INDEX TERMS Internet of Things, component architectures, modeling, simulation, IP networks.

I. INTRODUCTION

The research and development of Internet of Things (IoT) technology has promoted the deep change in the medical and health field. Relying on the wearable biomedical sensor technology, the wireless sensor network technology, the Internet technology and other key technologies in the Internet of things [1], the Community Medical Internet of Things (CMIoT) can be established. It is expected to change the traditional hospital centered medical mode so as to realize the family centered medical mode [2].

As the foundation of the CMIoT, the architecture can precisely define the whole network components and their relation, and ensure that the network construction follows the principle of unanimity. It is instructive to the design of the CMIoT system. At present, many scholars have carried out extensive researches on the IoT architecture. The IoT-A architecture proposed by Zorzi *et al.* [3] includes four layers such as wireless communication protocol, M2M API, IP and application. Ma *et al.* [4] proposed the IoT architecture including four layers: object sense layer, data exchange layer, information integration layer and application service layer. However, in the CMIoT environment, it not only requires sensor nodes to send data to the server via the Internet, but also requires the server to accurately locate sensor nodes and transmit controlling commands to them, and at the same time, the data transmission should not be affected by the change of network environment of sensor nodes. Especially body area network [5], home area network [6], community area network and even larger scale heterogeneous networks need to coexist in CMIoT. In the traditional IoT protocol conversion gateways, only the data conversion between different protocols is considered [7]–[9]. It is difficult to implement data path effectively when the node network environment changes in the subnet. Therefore, the architecture of CMIoT needs to be improved on the basis of current architecture.

As the next generation of Internet core technology, IPv6 network has a large address space, and can meet the requirement of the deployment of large-scale and high-density sensor network equipments. The application of IPv6 technology in IoT is an inevitable requirement for the development of IoT [10]. In this paper, we propose a kind of five-layer CMIoT architecture based on IPv6. At the same time, the paper focuses on the design of the mechanism and protocol format of the sensing/execution layer and the

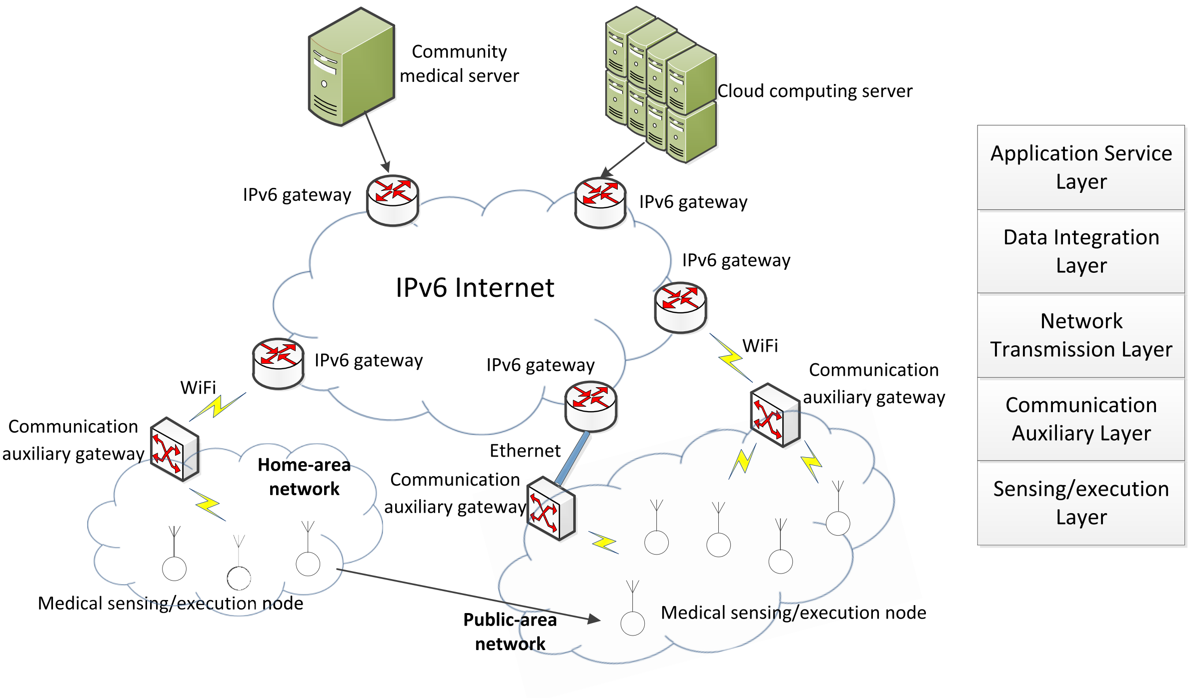

FIGURE 1. IPv6-based architecture of CMIoT.

communication auxiliary layer, analyzes the proposed CMIoT architecture which can effectively support the interconnection of sensor networks and IPv6 networks. Then, the Ptolemy II modeling environment is used to complete the modeling and simulation of the proposed CMIoT architecture. Finally, a prototype system will be built so as to verify the effectiveness of the proposed architecture.

II. ARCHITECTURE OF CMIoT

In the CMIoT environment, the health data of community residents carrying medical sensors should be uploaded to the medical server in a timely and effective manner through the IPv6 network. After collecting those data, the medical server transmits it to the cloud server for data integration, processing and storage, and at the same time, according to the data collected, the server will issue some warning or prompt information as needed.

A. SOME DEFINITIONS

Definition 2.1 (Medical Sensing/Execution Node): It is a node which physical layer and MAC layer, frame size and other aspects follow the IEEE 802.15.4 standard. It can collect and transfer human health data, receive information and execute commands. At the same time, it has the characteristics of low power consumption, low computing and storage capability, low transmission rate, short transmission distance and strong mobility.

Definition 2.2 (Medical Sensing/Execution Network): It is a communication network consisting of medical sensing/execution nodes.

Definition 2.3 (Communication Auxiliary Gateway): It is a device model which accesses the IPv6 backbone with WiFi, Ethernet and other means, can build a medical sensing/execution network, and at the time, realize the interworking between IPv6 network and medical sensing/execution network.

Definition 2.4 (Uplink Transmission): It is the process of transmitting data from a medical sensing/execution node to a medical server.

Definition 2.5 (Downlink Transmission): It is the process of transmitting data from a medical server to a medical sensing/execution node.

The CMIoT architecture is shown in Figure 1. There are two major problems that need to be addressed. One is the medical network of mobile nodes with strong mobility, and the unique identification of their identities. The second is to effectively transmit data to the IPv6 backbone and to receive data effectively from the IPv6 backbone. The mobility is that the medical sensing/execution node, which is wore on the human, and can be moved from one area to another. That is a quite common scene. Therefore the node has strong mobility. However the network built by the communication auxiliary gateway has limit range so that the network will be changed and the network address will be reassigned. It is hard for the medical server to find the node and communication with it. But with the recognition mechanism of medical sensing/execution nodes we proposed, the problem can be solved to adapt this mobility.

B. SENSING/EXECUTION LAYER

The sensing/execution layer is at the bottom of the CMIoT architecture, and composed of a series of sensory or execution components. The sensory or execution component uses various of biomedical sensing devices to collect human health data, and then transfers it to the medical server. And at the same time, it can receive the data transmitted by the medical server, and transmit the corresponding data to the outside through the small LED display, buzzer or other executing devices. In addition, these components are carried by people, and have strong mobility which leads to the dynamic change of the network environment in which they are located.

C. COMMUNICATION AUXILIARY LAYER

In the sensing/execution layer, the devices usually have the characteristics of low power consumption, low calculation and storage capability, etc. Their network usually uses simpler lightweight communication protocols such as ZigBee, Z-wave, and Wireless HART with the localization characteristic. These devices cannot be effectively identified in the Internet that runs the IP protocol and are difficult to communicate with devices in the Internet. Therefore, the communication auxiliary layer is used to build a bridge between the sensing/execution layer and the network transmission layer, and assist the devices in the Internet to recognize the device in the sensing/execution layer effectively. Meanwhile, its protocol conversion function is carried out to complete the data path between the Internet and the medical sensing/execution network.

D. NETWORK TRANSMISSION LAYER

The network transmission layer is a backbone network composed of devices that run the IPv6 protocol. These devices usually have high computing and storage performance. Generally, data transmission between devices is mainly based on wired Ethernet. It has the characteristics of high network bandwidth, large transmission range, fast transmission speed and stable transmission performance.

E. DATA INTEGRATION LAYER

Because the sensing/execution layer is usually large in number of devices and large in amount of data acquisition, the data integration layer needs to provide high performance computing and large capacity storage services so as to meet the needs of mass data storage and processing. Massive data processing usually needs big data analysis and data mining techniques to clean up data with errors, deletions, exceptions, and redundancies, and stores valid data in the data warehouse for providing support for the application service layer.

F. APPLICATION SERVICE LAYER

The application service layer implementation focuses on the utilization of data. It makes use of all kinds of information systems and platforms, and provides multiple personalized services including data display, query, statistical analysis, subscription and so on. At the same time, the necessary data can be sent to the sensing/execution layer devices to realize the feedback of the sensed data.

III. COMMUNICATION AUXILIARY GATEWAY

For the communication auxiliary gateway, there are three aspects of functions. First of all, it ensures the rapid establishment of the medical sensing/execution network. Secondly, it is necessary to assist medical servers to locate medical sensing/execution nodes effectively. Finally, it is necessary to realize the interconnection between medical sensing/execution network and IPv6 backbone network.

A. MEDICAL SENSING/EXECUTION NETWORK

For the medical sensing/execution network, the communication auxiliary gateway acts like a full-function device (FFD) [11] in the ZigBee network. The medical sensing/execution network is established by a communications auxiliary gateway which selects a channel and then initiates the entire network after power on. Moreover, in order to realize the rapid networking of sensing/execution nodes, the selection of network topology, the process of node access and the optimization of frame structure should be taken into account.

1) TOPOLOGICAL STRUCTURE

Because of the strong mobility of medical sensing/execution nodes, the network switching of nodes is relatively frequent. If the complex topology is adopted, the speed of network access is difficult to guarantee. The nodes are distributed in the residential or public areas, and the requirement of transmission range is not high. Therefore, it is suitable to choose the star topology with the communication gateway as the core, as shown in Figure 2.

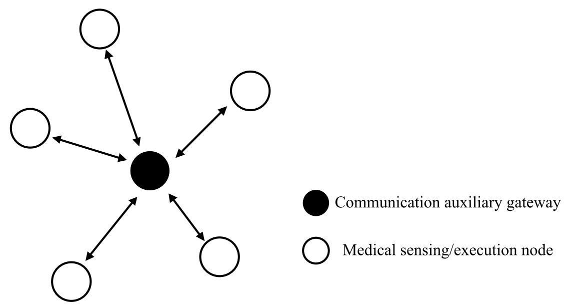

FIGURE 2. Medical sensing/execute node network topology.

2) NETWORKING PROCESS

In order to network, the medical sensing/execution node needs to send the networking request to the communication auxiliary gateway. The networking request interaction process is shown in Figure 3.

Step 1: New node requests to network.

The new node firstly sends the registration message to the communication auxiliary gateway. The registration message format is shown in Figure 4.

- Message type: 4 bits, defaults to 0001.
- Reserved bits: 4 bits, used to expand.

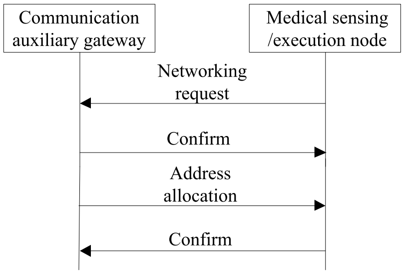

FIGURE 3. Medical sensing/execution node networking request interaction diagram.

0–4	4–8	8–16	16–32
Message type	Reserved bits	Serial number	Destination address
Node MAC address			

FIGURE 4. Registration message format.

- Serial number: 8 bits, unique sequence identifier of a frame.
- Destination address: 16 bits, network address of the communication auxiliary gateway in medical sensing/execution network.
- Node MAC address: 64 bits, MAC address of the medical sensing/execution.

Step 2: Networking confirmation.

After receiving the registration message, the communication auxiliary gateway needs to send a confirmation message to the networking request node, as shown in Figure 5. Its message type defaults to 0010.

0–4	4–8	8–16
Message type	Reserved bits	Serial number

FIGURE 5. Networking confirmation message format.

0–4	4–8	8–16	16–32
Message type	Reserved bits	Serial number	Node network address

FIGURE 6. Networking permission message format.

Step 3: Address allocation.

The communication auxiliary gateway sends the networking permission to the networking request node so as to assign a network address to the networking request node in the order in which the address is incremented. The message format is shown in Figure 6.

- Message type: 4 bits, defaults to 0011.
- Node network address: 16 bits, the network address assigned to the networking request node.

Step 4: Networking completeness confirmation.

The networking request node returns the networking completeness confirmation message to the communication auxiliary gateway, and the networking request node joins the network.

B. HETEROGENEOUS NETWORK INTERCONNECTION

Because of the difference of protocol systems, IPv6 network nodes and medical sensing/execution nodes cannot transmit data directly. There are two major factors in the communication barrier. One is that the network address of the medical sensing/execution node is local, and cannot be uniquely identified by the IPv6 network. Two is that their frame format is different, e.g., the frame length of the IPv6 maximum transfer unit (MTU) is equal or greater than 1280B, and the frame length in the medical sensing/execution network protocol following the IEEE 802.15.4 standard is not more than 127B [12]. Therefore protocol conversion and transmission efficiency optimization design are needed between the two different networks.

1) RECOGNITION MECHANISM OF MEDICAL SENSING/EXECUTION NODES

For the unique identification problem of low power IoT nodes, the 6LoWPAN working group is dedicated to introducing IPv6 into low power networks in order to realize the interconnection of low power network and IPv6 network. The research focuses on the design of the adaptation layer between the low power network MAC layer and the IPv6 network layer [13]. In addition, to support the application of IPv6 in low power networks, Xiao *et al.* [14] designed a IPv6 light weight and tree-based forwarding model TFAD, and then proposed IPv6 address compression based on hierarchical structure IACH which uses the IPv6 address inheritance relationship of parent and child nodes in hierarchical structure to make IPv6 packets be transmitted in the most streamlined address form. Hui and Culler [10] made it possible for IPv6 to be applied to low power networks with IPv6 address compression, address configuration, neighbor discovery, routing mechanisms and so on.

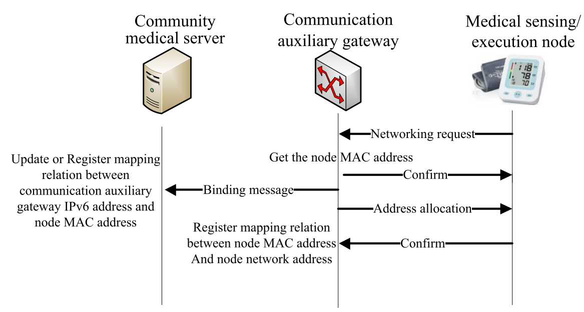

FIGURE 7. Recognition mechanism of medical sensing/execution node.

Nevertheless, to make IPv6 directly be applied to low power networks is still in theoretical research stage, and related products have not yet been promoted. Aiming at the problem of node unique identification in low power networks, we propose a unique identification mechanism with the help of communication auxiliary gateway, as shown in Figure 7, so as to effectively solve the problem of IPv6 network identification for low power network nodes.

The main implementation process of the recognition mechanism is as follows:

Step 1: The communication auxiliary gateway generates the EUI-64 identifier by performing the IPv6 stateless address automatic configuration protocol while establishing the medical sensing/execution network. Combined with the address prefix declared by the IPv6 router, an IPv6 global unicast address is obtained.

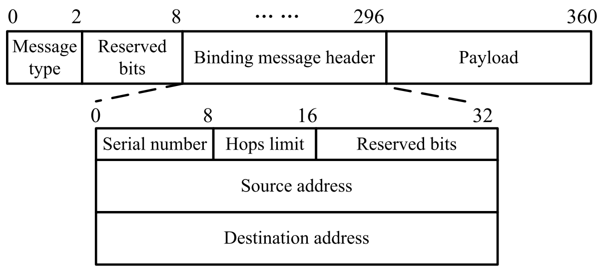

FIGURE 8. Binding message format.

Step 2: When there is a new networking request, the communication auxiliary gateway also needs to obtain the content of the node MAC address field in the registration message at the same time of receiving the node register message. And it sends the binding message to the medical server in the IPv6 network for binding the auxiliary gateway IPv6 address and the node MAC address, as shown in Figure 8.

- Message type: 2 bits, defaults to 00.
- Binding message header: 288 bits, includes serial number (8 bits, unique sequence identifier of a frame), hops limit (8 bits), reserved bits (16 bits), source address (128 bits, IPv6 address of a communication auxiliary gateway) and destination address (128 bits, IPv6 address of a server).
- Payload: 64 bits, the medical sensing/execution node MAC address obtained from the registration message.

Step 3: After receiving the binding message, the medical server obtains the source address field (IPv6 address of a communication auxiliary gateway) and the payload field (medical sensing/execution node MAC address), and lookups the mapping table of communication auxiliary gateway IPv6 address and node MAC address as shown in Table 1. If the same address exists in the node MAC address field, the corresponding communication auxiliary gateway IPv6 address is updated, and otherwise, a new record is appended.

TABLE 1. Mapping table of communication auxiliary gateway IPv6 address - medical sensing/execution node MAC address.

IPv6 address	MAC address
2001:8::5513:2B1D:332F:1132	FE-80-1B-A8-34-1D-A3-B5
2001::4413:2B1D:368F:1D1F	FE-80-1B-A8-36-4B-A7-B6
…	…

Step 4: The communication auxiliary gateway sends networking permission message to the networking request node for assigning network address. After receiving the confirmation message of the networking request node, the communication auxiliary gateway registers the MAC address of the networking request node and the assigned network address information in the mapping table of node MAC address – node network address, as shown in Table 2.

TABLE 2. Mapping table of node MAC address - node network address.

MAC address	Network address
FE-80-1B-A8-34-1D-A3-B5	0x0001
FE-80-1B-A8-36-4B-A7-B6	0x0002
…	…

So far, that is to complete the identification of a medical sensing/execution node and ensures that the medical server locates the medical sensing/execution node effectively. Furthermore, regardless of whether the medical sensing/execution node re-network due to movement or not, the network address changes can be uniquely identified by the medical server in the IPv6 network. However, because of the difference of protocol systems between IPv6 network and medical sensing/execution network, the frame format and the frame size limit are different, and therefore the protocol conversion and adaptation are needed.

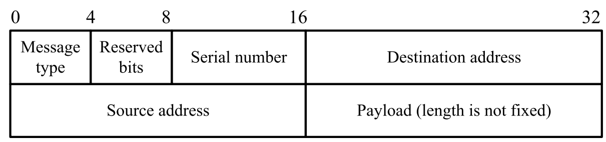

FIGURE 9. Data message format.

2) PROTOCOL FRAME FORMAT CONVERSION

In the medical sensing/execution network, the information collected by the medical sense node is encapsulated as a data message and transmitted to the communication auxiliary gateway, as shown in Figure 9.

- Message type: 4 bits, defaults to 0100.
- Destination address: 16 bits, the network address of the receiving node in the medical sensing/execution network.
- Source address: 16 bits, the network address of the sending node in the medical sensing/execution network.
- Payload: the length is variable, but not more than 121B, that is, the data collected by the medical sensing/execution node.

Data transmission of communication auxiliary gateway and IPv6 network adopts IPv6 message form, in which IPv6 header may adopt IPv6 standard header or IPv6 compressed header form [12], [18]. The message is encapsulated in a WiFi data frame format defined by the IEEE 802.11 standard (or Ethernet data frame format defined by the IEEE 802.3 standard), as shown in Figure 10, and then transmitted to the IPv6 gateway.

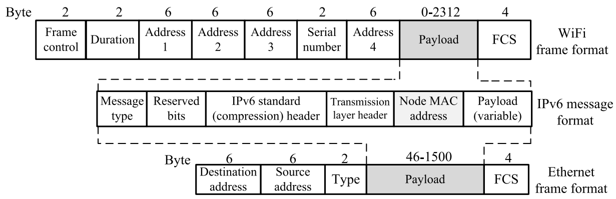

FIGURE 10. IPv6 message and encapsulation format.

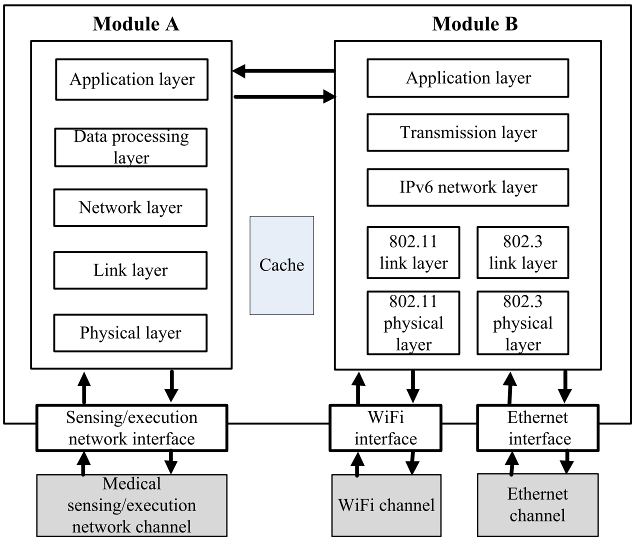

FIGURE 11. Protocol conversion mode of communication auxiliary gateway.

With regard to IPv6 message packets, the message type is 2 bits, e.g., 01 represents the IPv6 standard header of 40B, and 10 represents the IPv6 header in a compressed format. In addition, in the message of the transmission layer, the former 64 bits are designed as a fixed field, that is, the medical sensing/execution node MAC address field. From the foregoing analysis, it is necessary to complete the conversion of frame formats by the communication auxiliary gateway to realize the data transmission between the medical sensing/execution network and the IPv6 network. The communication auxiliary gateway protocol conversion model is shown in Figure 11. The cache is used to store the map table between node MAC address and node network address and other temporary data needed. The sensing/execution network interface, the WiFi interface and the Ethernet interface are used to send and receive messages, WiFi frames and Ethernet frames in the medical sensing/execution network. A module and B module respectively layer by layer unpack or package the data packets of different structures in heterogeneous network environment.

3) DATA PATH MODEL

A data path model based on the communication auxiliary gateway is shown in Figure 12. Under the precondition that the medical sensing/execution node completes the networking and binding operation, the data uplink transmission process is as follows.

Step 1: The medical sensing/execution node encapsulates the data in the data message format and sends it to the communication auxiliary gateway.

Step 2: The communication auxiliary gateway receives the message from the medical sensing/execution network interface and transfers it to the module A. When the message reaches the link layer, if the message type is 0100, the received message is determined as a data message. And then the payload data is extracted according to the corresponding message format and transmitted to the network layer, and the message type is put into its cache.

Step 3: The network layer receives the packet and reads the destination address field. If it is not its own network address, the transfer operation is performed according to the corresponding destination address; otherwise, step 4 will be executed.

Step 4: The network layer continues to read the source address of the packet and lookup the mapping table of node MAC address - node network address. If no corresponding MAC address matches the source address, the message is dropped. Otherwise, the corresponding MAC address and network layer payload are transmitted to the data processing layer.

Step 5: The data processing layer integrates the MAC address and the network layer payload into an integrated data, and transmits it to the application layer.

Step 6: The application layer encapsulates the integrated data into the application layer data, and transfers it to the module B through the serial port.

Step 7: Module B receives data from the application layer, and transmits it to the transmission layer.

Step 8: The transmission layer receives the data, and after appending the transmission layer header, transmits it to the IPv6 network layer.

Step 9: The IPv6 network layer reads the messages in the cache. If the message type value is 0100, it is determined as a data message, and then the IPv6 standard header (or IPv6 compression header) is appended. The destination address is the medical server IPv6 address. At the same time, the message type of the IPv6 message is set to 01 (or 10), and then transmitted to the 802.11 (or 802.3) link layer.

Step 10: The 802.11 (or 802.3) link layer encapsulates the IPv6 message packet into a WiFi (or Ethernet) frame according to the specification standard, and transmits it to the 802.11 (or 802.3) physical layer.

Step 11: The 802.11 (or 802.3) physical layer appends the synchronization code so as to generate a physical frame, and sends it to the WiFi channel (or Ethernet link). After received by the corresponding IPv6 gateway and uniformly converted to the Ethernet frame format, the physical frame is routed through the IPv6 network and sent to the medical server.

Step 12: The medical server receives the Ethernet frame, and after unpacking, extracts the IPv6 message for the transmission layer message. According to the first 64 bits of the payload in the transmission layer message, the node MAC address is extracted. The corresponding data information is

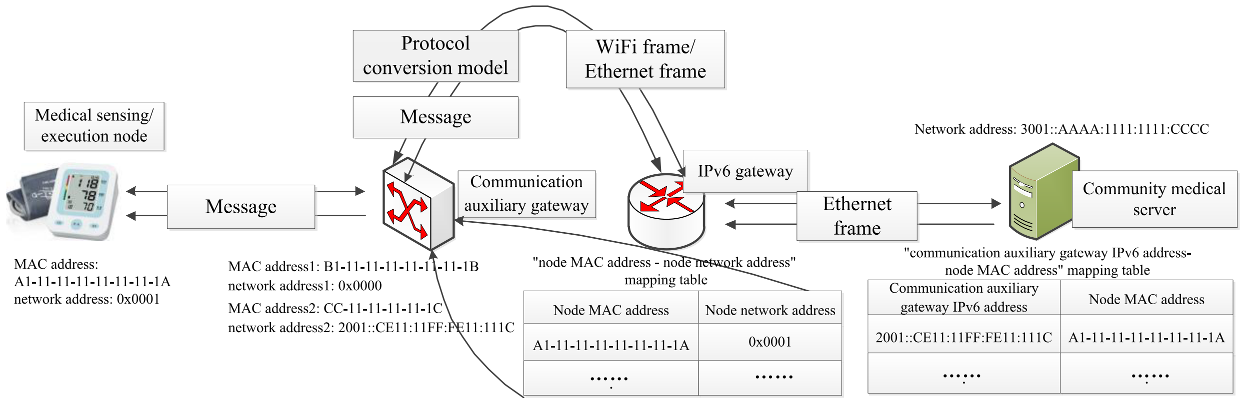

FIGURE 12. Data path model.

obtained, and the mapping relation between the communication auxiliary gateway IPv6 address and the node MAC address is recorded.

The data downlink transmission process is as follows.

Step 1: The medical server determines the sending destination node MAC address, and lookups the mapping table of communication auxiliary gateway IPv6 address – node MAC address. If the corresponding MAC address is not found, it terminates; otherwise goes to Step 2.

Step 2: The communication auxiliary gateway IPv6 address corresponding to the node MAC address is got. The node MAC address and the transmission data are encapsulated as the payloads in the transmission layer message. Subsequently, the IPv6 message packet is encapsulated with the auxiliary gateway IPv6 address as the destination address so as to get an Ethernet frame. Routed through the IPv6 network, it is sent to the IPv6 gateway.

Step 3: According to the networking mode of the communication auxiliary gateway, the IPv6 gateway transmits it in a WiFi (or Ethernet) frame to the communication auxiliary gateway WiFi (or Ethernet) interface, which is then transmitted to module B.

Step 4: The frame payload is extracted from the 802.11 (or 802.3) link layer of module B, and sent to the IPv6 network layer.

Step 5: After checking the message type and confirming that it is a IPv6 message, according to the format of IPv6 messages, the IPv6 network layer unpacks the IPv6 message, and extracts the payload and send it to the transmission layer.

Step 6: After unpacked by the transmission layer, the transmission layer payload data is extracted and sent to the application layer. Then the data is transferred to the application layer of module A through the serial port.

Step 7: The application layer of module A receives the data and transmits it to the data processing layer. The data processing layer divides the received data into two parts: the node MAC address and the actual data information. According to the node MAC address, the application layer lookups the mapping table of node network address - node MAC address. If no corresponding node network address is found, it terminates; otherwise goes to Step 8.

Step 8: The data processing layer transmits the node network address and the actual data information to the network layer. The network layer takes the node network address as the destination address and the actual data information as the payload, and encapsulates them into a data message. Through the medical sensing/execution network interface, it is sent to the medical sensing/execution network channel, which is finally received by the corresponding medical sensing/execution node.

IV. MODELING AND VERIFICATION OF CMIoT ARCHITECTURE

The design of the CMIoT architecture focuses on the rapid networking of medical sensing/execution network, the unique identification of mobile node identity under IPv6 network environment, and the interconnection between the medical sensing/execution network and the IPv6 network. Based on the Ptolemy II modeling environment, the CMIoT architecture modeling and simulation are carried out to verify that the CMIoT architecture can effectively support the interconnection.

A. PTOLEMY II

The Ptolemy II modeling environment was developed by Lee [15] It is mainly used for modeling, simulation and design of parallel real-time embedded systems. Ptolemy II modeling tools define different computing models for different system behaviors, and solve the modeling problem of heterogeneous systems based on hierarchical modeling theory [16]. The simulation of sensor network needs accurate description and analysis of communication channel, sensor node, ad-hoc network protocol, local strategy, media access control protocol, and energy consumption in sensor network. Ptolemy II has a very rich set of modeling mechanisms that can be used to build complex models of sensor nodes and transmission efficiency. Ptolemy II uses component-based model building methods to support role-based approaches to define network

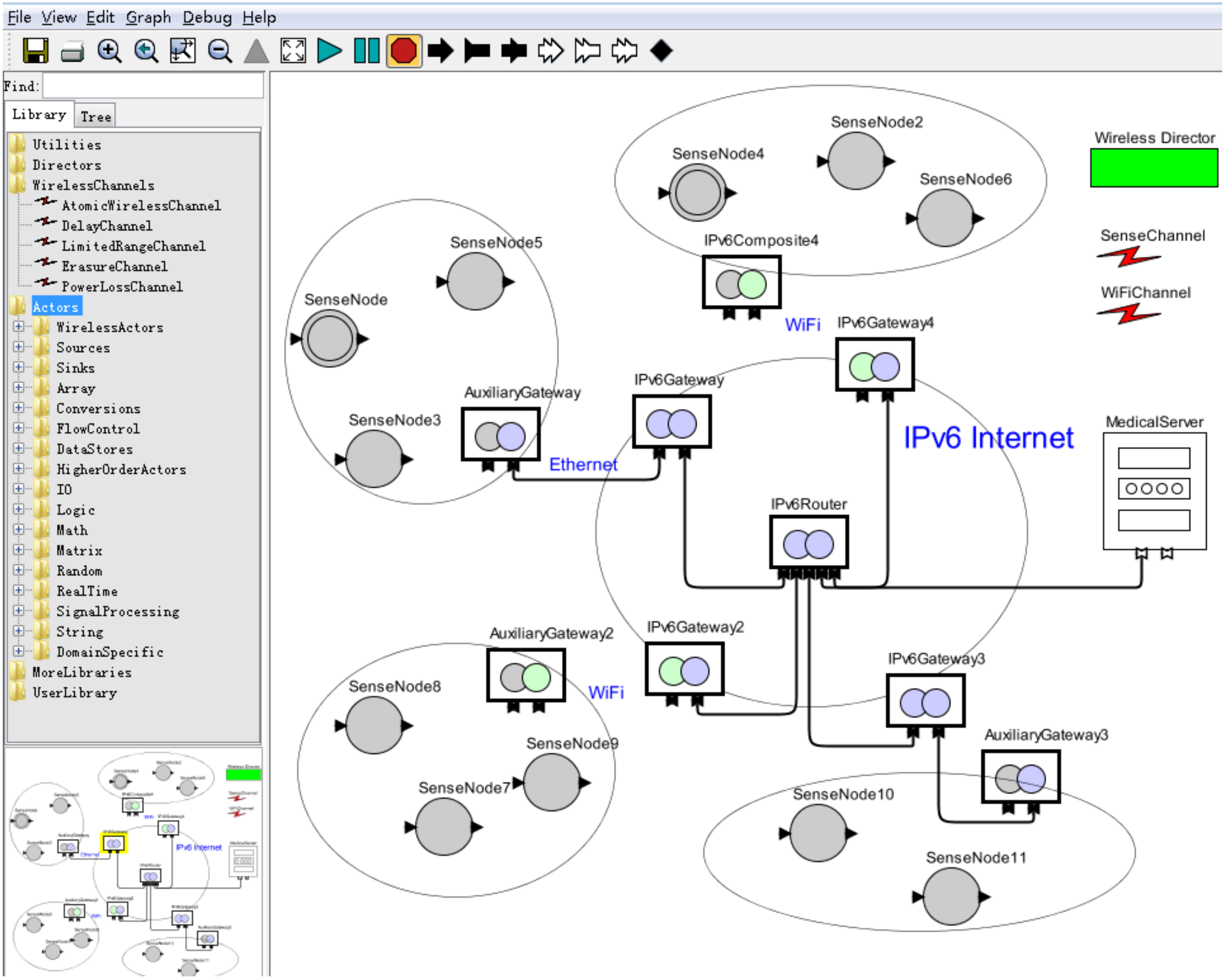

FIGURE 13. **CMIoT architecture model based on Ptolemy II.**

nodes, wireless communication channels, physical media (such as sound channels), and wired subsystems [17].

The CMIoT architecture we proposed is a kind of heterogeneous network architecture, i.e., different communication modes coexists in the system. To realize the heterogeneous network interconnection is the main problem that we need to solve. In order to vividly show the CMIoT's data path in the heterogeneous network system, we choose Ptolemy II to build our model.

- Firstly, the Ptolemy II environment provides support for hierarchically combining a large variety of models of computation. In contrast to most of other design tools, Ptolemy II was developed from the outset to address heterogeneous systems.
- Secondly, Ptolemy II has a very rich set of modeling mechanisms that can be used to build complex models of sensor nodes and transmission efficiency.
- Thirdly, Ptolemy II includes a sophisticated type system that includes aggregate types like records, which can also be used to construct packets with arbitrary payloads, and other modeling capabilities like packet losses, battery power, collisions and so on.
- In addition to modeling channel delays, the wireless domain can model power loss, interference, noise, and occlusion. It can also model directional antenna gain, mobile transmitters and receivers. All of these are quite suitable for the CMIoT demands.

B. CMIoT ARCHITECTURE MODEL

Based on the Ptolemy II modeling environment, the top level model of the CMIoT architecture is constructed, as shown in Figure 13. The node communication in the medical sensing/execution network is completed through the *SenseChannel* channel. There is a communication auxiliary gateway for every medical sensing/execution network, which completes the connection with the IPv6 gateway via the *WiF iChannel* or *Ethernet* link. In IPv6 backbone, devices are wired to Ethernet. The running time, sequence and other attributes of the whole model are controlled by the *Wireless-Director* component.

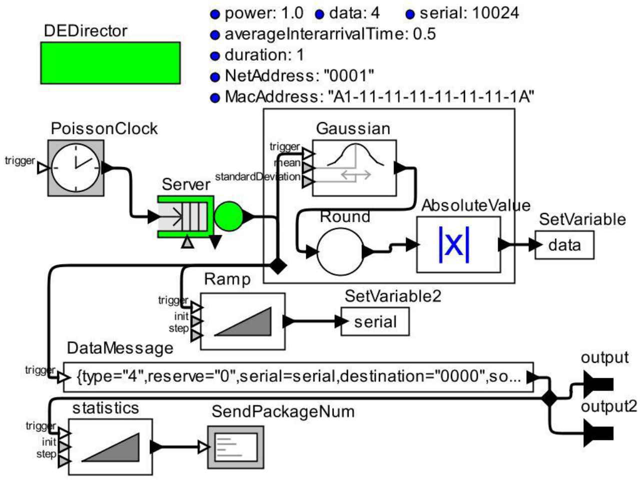

FIGURE 14. **Uplink transmission function model of the medical sensing/execution node.**

1) FUNCTION MODEL DESIGN OF MEDICAL SENSING/EXECUTION NODE

The main functions of the constructed medical sensing/execution node include generating data messages for uplink transmission and receiving the data transmitted by the medical server. The uplink transmission function model of the medical sensing/execution node is shown in Figure 14, in which the *PoissonClock* role generates a trigger event based on the Poisson distribution function to control the generation of the data messages, the three roles including *Gaussian*, *Round* and *AbsoluteValue* work together to generate random positive integer messages, and the *DataMessage* component encapsulates the data message and sends it to the output port so as to complete the generation and transmission of data messages.

The data receiving function model of medical sensing/execution nodes is shown in Figure 15. Ptolemy II provides two roles, e.g., *RecordDisassembler* and *RecordAssembler*, for the decomposition and encapsulation of the data message. After receiving the message, the *RecordDisassembler* role is used to extract the destination address and the message type field. The payload data is extracted when it is confirmed to be a data message sent to the current node.

Besides, as shown in Figure 16, in the medical sensing/execution node's moving model, the node can move in an elliptical trajectory, i.e., [$sin(x)*200+200$; $sin(y)*200+300$]. It can be changed and then the trajectory will change. When the node moves, it maybe enters another network and rebuilds the connection with another communication auxiliary gateway. Through the recognition mechanism, the communication auxiliary gateway will update its mapping table and build up the data path to IPv6 network.

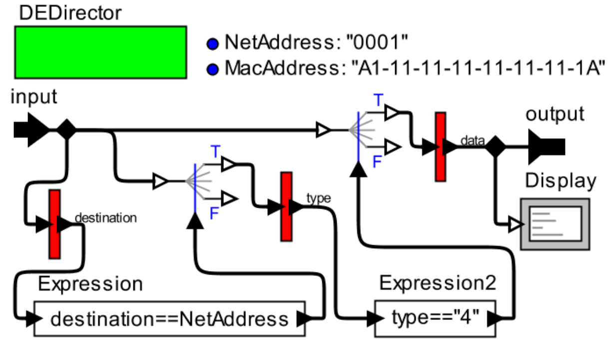

FIGURE 15. **Data receiving function model of medical sensing/execution nodes.**

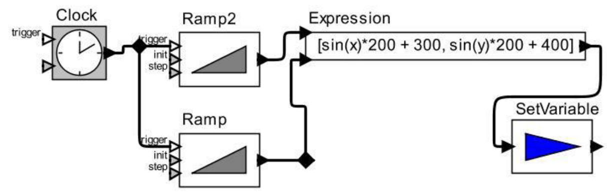

FIGURE 16. **Moving model of medical sensing/execution nodes.**

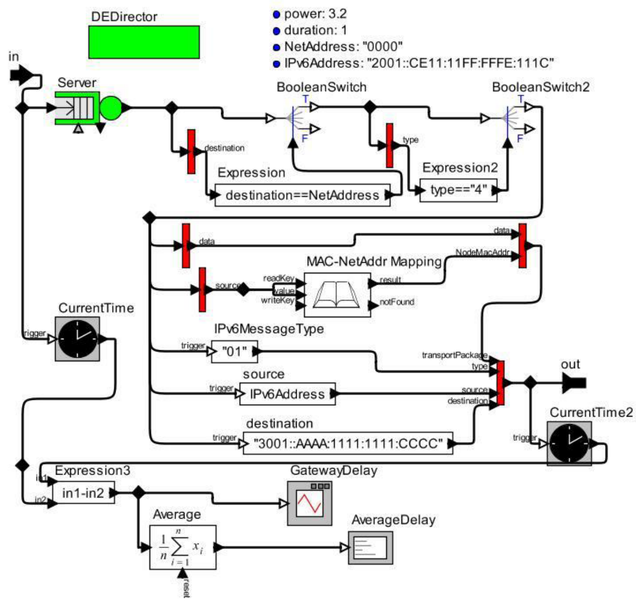

FIGURE 17. **Uplink transmission function model of communication auxiliary gateway.**

2) FUNCTION MODEL DESIGN OF COMMUNICATION AUXILIARY GATEWAY

The uplink transmission function model of a communication auxiliary gateway is shown in Figure 17. After receiving the message, the communication auxiliary gateway also extracts the destination address and the message type. When determining the data message to be sent to itself, the communication auxiliary gateway can extract the data in the message format, and then encapsulates IPv6 message packet. First, it lookups the mapping table of the node MAC address - node network address (MAC-NetAddr Mapping). If the corresponding node MAC address is detected, the payload data will be encapsulated in a transmission layer message. Then, the source IPv6 address and the destination IPv6 address will be encapsulated in the IPv6 message packet according to the message type. This model is designed to realize the data path simulation requirements. In order to simplify the model, IPv6 message packet integrity and link layer encapsulation have not been carried out. In addition, the *Dictionary* role is used in this model to complete the function of the mapping table. The Dictionary role stores the data elements in the form of (*key*, *value*) pairs, and provides 9 external ports such as *ReadKey*, *value*, *writeKey*, *result*, *notF ound* and so on. Data query can input keywords through *readKey* port and output corresponding data by the *result* port. The data storage is accomplished by entering*keys* and *value*s simultaneously to the *writeKey* and *value* ports.

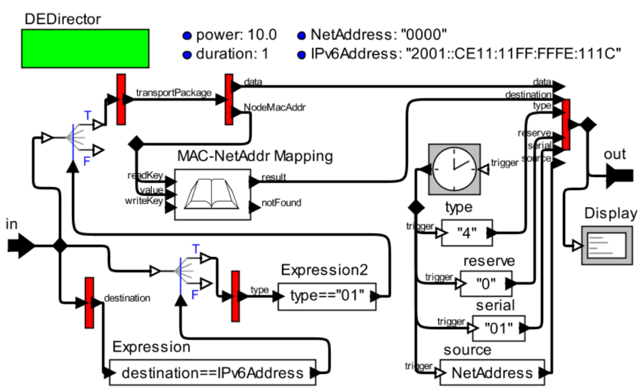

FIGURE 18. Downlink transmission function model of the communication auxiliary gateway.

The downlink transmission function model of a communication auxiliary gateway is shown in Figure 18. For the IPv6 message received, the communication auxiliary gateway unpacks layer by layer. Based on the received node MAC address, it lookups its mapping table to obtain the node network address. Then, the data message is encapsulated and sent to the corresponding medical sensing/execution node.

3) FUNCTION MODEL DESIGN OF IPv6 GATEWAY AND IPv6 ROUTER

For IPv6 routers, the router is simply designed to act as a repeater on the data transmission path without routing mechanisms. The transmission delay is simulated by connecting buffers between the input port and the output port, as shown in Figure 19. As for the IPv6 gateway, because it has both wireless and wired access modes, it can combine the two roles of *WirelessToWired* and *WiredToWireless* provided by Ptolemy II, so as to accomplish the conversion between wire transmission and wireless transmission, as shown in Figure 20.

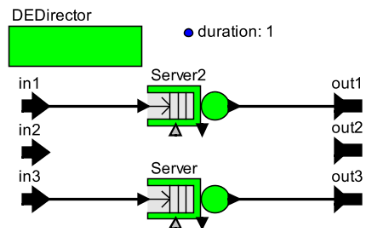

FIGURE 19. IPv6 router function model.

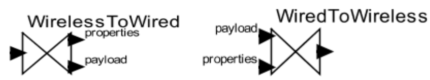

FIGURE 20. WirelessToWired and WiredToWireless roles.

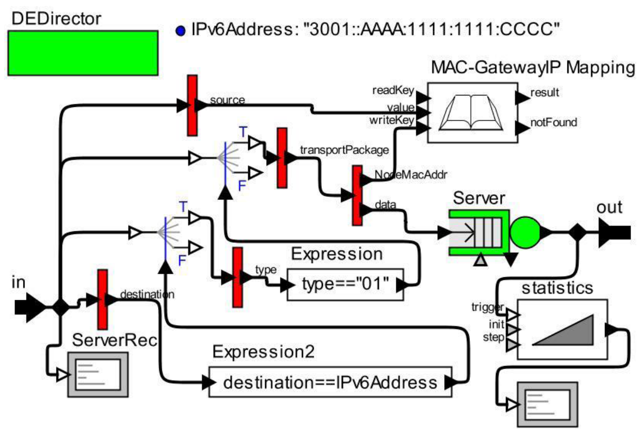

FIGURE 21. Data receiving function model of the medical server.

4) FUNCTION MODEL DESIGN OF MEDICAL SERVER

The medical server function model is also divided into two sub models: data receiving model and data generating/transmitting model. The former is shown in Figure 21. For the received message, when the medical server unpacks it and extracts the transmission layer message, it needs to extract the corresponding medical sensing/execution node MAC address field, and generate the (*key*, *value*) pair with the source IPv6 address in the message. The (*key*, *value*) pair is input through the *writeKey* and value ports of the *Dictionary* role, and stored in mapping table of communication auxiliary gateway IPv6 address - node MAC address. Then, the server continues to unpack the message and extract the payload data.

The downlink transmission function model of the medical server is shown in Figure 22. The *PoissonClock* role generates a trigger event based on the Poisson distribution function to control the generation of IPv6 messages. The medical server must first determine the destination node MAC address, and uses it as the input of the *readkey* port of the *Dictionary* role, so as to lookup the mapping table of communication auxiliary gateway IPv6 address - node MAC address for obtaining the IPv6 address of the communication auxiliary gateway. At the

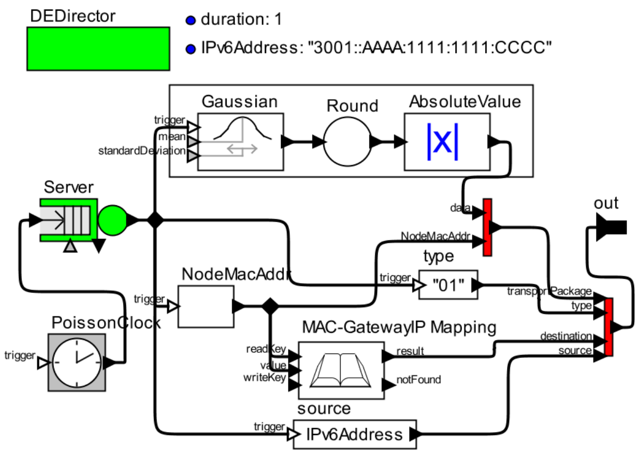

FIGURE 22. Data generating/transmitting function model of the medical server.

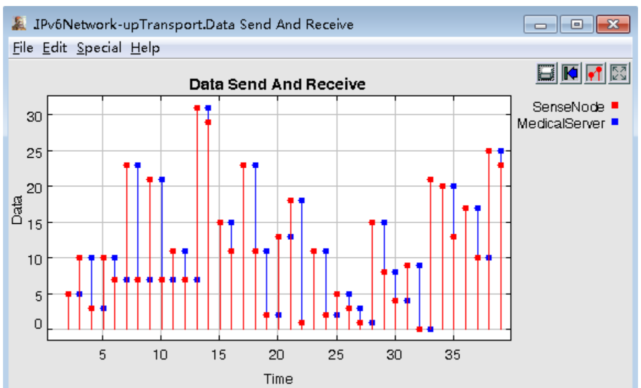

FIGURE 23. Ideal uplink data transmission.

same time, a random data is generated as the application layer data and encapsulated to form an IPv6 message, which will be sent to the IPv6 network.

C. MODEL SIMULATION AND VERIFICATION

Unlike static structure design, e.g., UML modeling or 3D volumetric modeling, the models built in Ptolemy II are dynamic and executable. According to the model constructed, the uplink transmission data path from medical sensing/execution nodes to the medical server and the downlink transmission data path from the medical server to the designated medical sensing/execution node are verified.

1) VERIFICATION OF UPLINK DATA PATH

When the model runs, according to Poisson distribution, the medical sensing/execution node irregularly generates a data message packet at an average time of 0.5*s*. The messages are transmitted to the medical server via the communication auxiliary gateway and the IPv6 network, as shown in Figure 23. After a certain network delay, the server can normally receive data from the medical sensing/execution nodes. In the case of a certain packet loss rate of the channel, there is the loss of individual data. However, most of the data can be received normally, as shown in Figure 24.

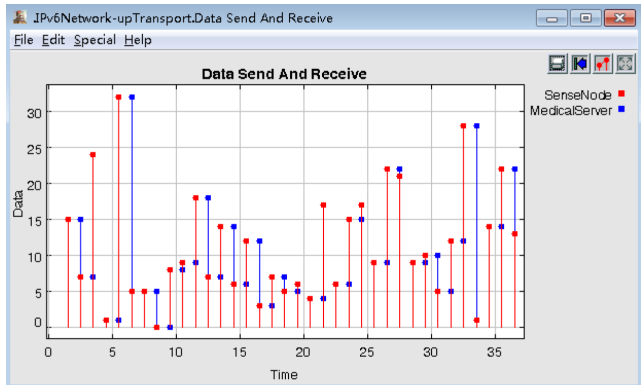

FIGURE 24. Uplink data transmission with a certain packet loss rate.

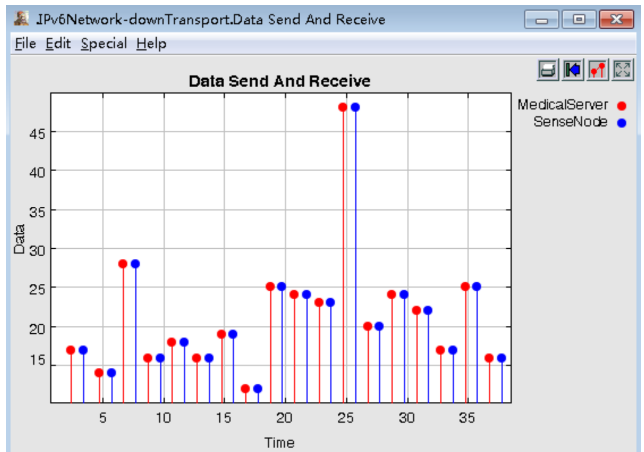

FIGURE 25. Ideal downlink data transmission.

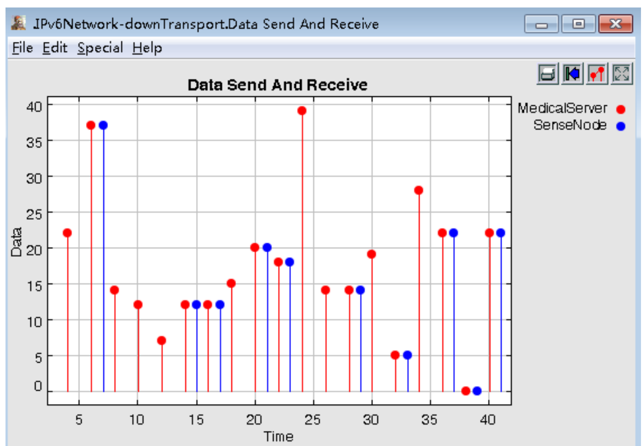

FIGURE 26. Downlink data transmission with a certain packet loss rate.

2) VERIFICATION OF DOWNLINK DATA PATH

Ideally, the downlink transmission results are shown in Figure 25. The medical server can accurately transfer data to the designated medical sensing/execution nodes, and the medical sensing/execution nodes can receive data normally. However, in the channel with a certain packet loss rate, there are still more data which can be received normally, as shown in Figure 26. The availability of the downlink transmission

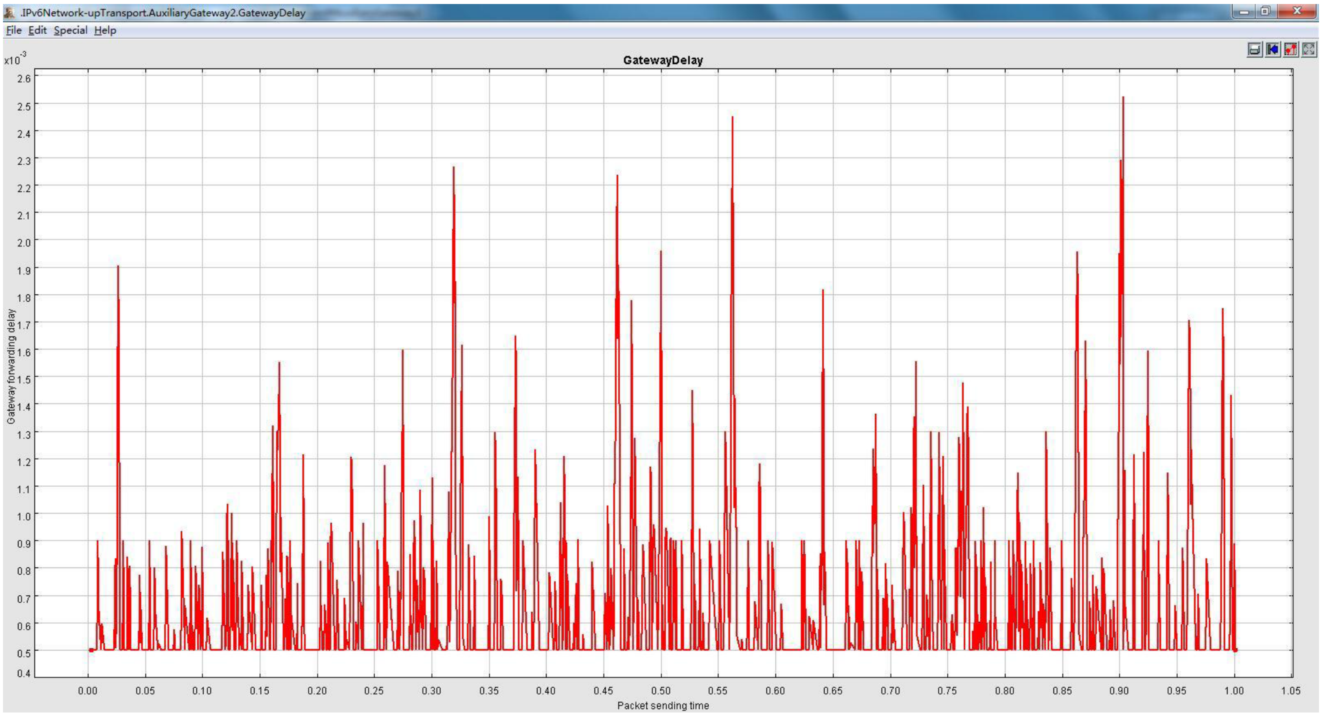

FIGURE 27. Forwarding delay of communication auxiliary gateway.

data path is thus verified. With the assistance of the communication auxiliary gateway, the IPv6 network nodes can effectively transmit data to the medical sensing/execution nodes. The interconnection between heterogeneous networks is realized.

3) VERIFICATION OF FORWARDING DELAY

In order to verify the forwarding delay of the communication auxiliary gateway, the medical sensing/execution node is configured to produce message packages with the average rate of $1ms$ and sends about one thousand packages. The communication auxiliary gateway will record the time when it receives the package and sends the package. The model is run to get the delay for each package, as shown in Figure 27. To use the average component to compute the average forwarding delay, the result is $0.746ms$.

4) VERIFICATION OF PACKET LOSS

The number of packages that are sent and received is recorded through the statistics component. Through adjusting the parameter of the *PoissonClock* component in the model of the communication auxiliary gateway, the package loss is tested in the different running scenes where the medical sensing/execution node sends different numbers of packages, such as 1003, 3022, 5043, 7113, 10023, and the numbers of received packages are recorded in the model of medical server. The package loss is shown in Table 3, and the average package loss rate is 0.09%.

TABLE 3. Packet loss.

Number of sending packets	Number of losing packets
1003	1
3022	4
5044	3
7113	5
10023	7

V. CMIoT PROTOTYPE SYSTEM

A. MEDICAL SENSING/EXECUTION NODE

In order to verify the CMIoT architecture model, we build a prototype system, as shown in Figure 28, in which some sensors are used, e.g., the temperature sensor DS28B20 is used to measure body temperature in a range [−55, 125], the blood pressure sensor is used to collect body blood pressure data. In order to transfer the sensing data to the server, the CC2530 chip combined with the Z-Stack communication protocol stack is used as a communication module, which is manufactured by Texas Instruments Company. With excellent transceiver performance, enhanced 8051 CPU, programmable flash memory, especially the low power consumption, it is quite suitable for CMIoT.

B. COMMUNICATION AUXILIARY GATEWAY

The communication auxiliary gateway is composed of three main modules such as STM32 board, sink node, and

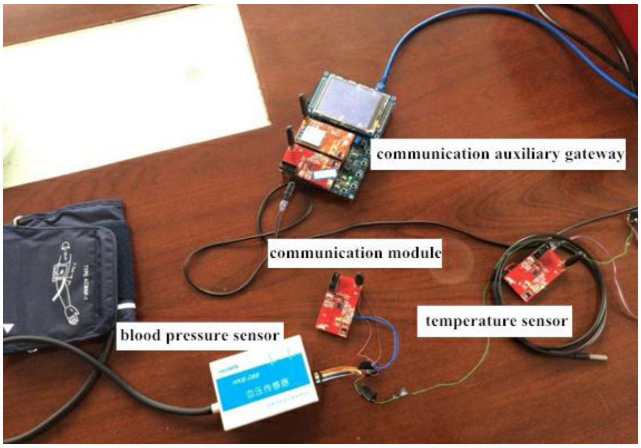

FIGURE 28. Real model of CMIoT.

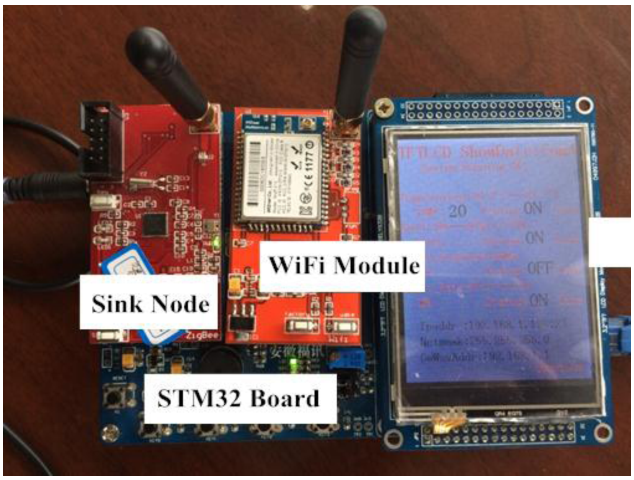

FIGURE 29. Communication auxiliary gateway.

WiFi wireless communication module. More specifically, it consists of STM32 (STM32F107 series) micro-processing chip combined with LWIP communication protocol stack, CC2530 chip combined with Z-Stack communication protocol stack, WiFi wireless communication module, external interface circuit, flash module, RAM module, power module, and Ethernet interface. The real communication auxiliary gateway model we designed is shown in Figure 29.

The structure of the communication auxiliary gateway is shown in Figure 30. The STM32F107 devices provide an Media Access Controller (MAC) for Ethernet communications through an industry-standard Media-Independent Interface (MII), and require an external Physical Interface Device (PHY) to connect to the physical LAN bus (twisted-pair, fiber, etc.). The PHY chip TLK110 is used as the single port 10/100Mbs Ethernet PHY. The WiFi module is a WizFi210 communication module which has a Universal Asynchronous Receiver/Transmitter (UART) interface and can connect with STM32 devices. The CC2530 module in the communication auxiliary gateway is used as a sink node to receive the data packages from the medical sensing/execution network through Z-Stack communication protocol stack. The data packages can be unpacked layer by layer, and then the application data are extracted and sent to the STM32 device through the UART interface. In the STM32 chip, we make use of the LWIP communication protocol stack, which is a widely used lightweight TCP/IP stack designed by Adam Dunkels in the Swedish Institute of Computer Science. The LWIP's IP layer is modified so as to support the IPv6 protocol.

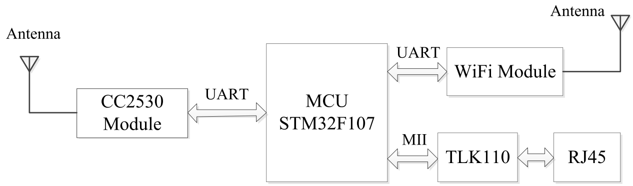

FIGURE 30. Communication auxiliary gateway.

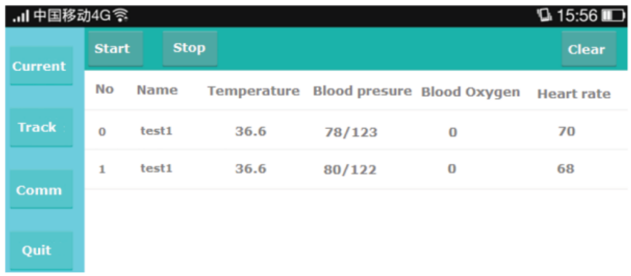

FIGURE 31. Data query of mobile terminal.

C. TESTING

To effective collect and store the data from medical sensing/execution network, the medical server is used to get the data through IPv6 network and store them in a MySQL database. In order to make the medical personnel expediently check the health data, two terminal modes (Ethernet/WiFi) are supported, i.e., personal computer and mobile device, as shown in Figure 31. The results shows that it can successfully realize the data path between medical sensing/execution network and IPv6 network.

VI. CONCLUSIONS AND FUTURE WORKS

The applications of IPv6 in IoT are the trend of the times. In this paper, an application branch of IoT-CMIoT is taken as the breakthrough point, and its five-layer architecture based on IPv6 is proposed. We propose an efficient solution mechanism for peer to peer subnet identification problem for IPv6 networks. At the same time, a bidirectional transmission data path model is designed based on the communication auxiliary gateway. And Ptolemy II modeling environment is used to build and validate the CMIoT architecture model.

It should be pointed out that there are still many key issues that need to be further studied in CMIoT architecture. When the number of nodes in a medical network is large enough, some issues, e.g., how to efficiently store and retrieve the mapping table in the communication auxiliary gateway and the medical server, fragmentation and reorganization of IPv6 message packets during downlink transmission, routing mechanism of IPv6 network oriented to IoT, will be the focus of the future research work.

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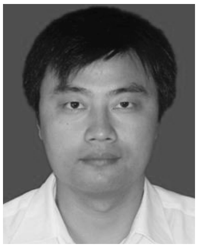

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