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A Survey on the Progress of Testing Techniques and Methods for Wireless Sensor Networks

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ABSTRACT Information-centric wireless sensor networks' test bed is of vital significance. As a novel communication model, it can effectively test and reliably assess different algorithms, protocols, and applications of wireless sensor networks before deployment. Furthermore, detecting problems, ensuring stable operations, and reducing maintenance costs can also be attained. It is a promising architecture. Through the tests of the platform, new ideas are provided for the development of wireless sensor networks of the Internet of Things (IoT) and for the improvement of the performances of the IoT. An information-centric network is a promising branch of future Internet architecture, and its naming, naming routing, and intra-network caching are also suitable for wireless sensor networks. Recently, with the integration of such different key technologies as micro-sensor, communication, and simulation, test beds are becoming increasingly heterogeneous and complicated in large scale. Because of this, it is essential to know how to build a functional test bed by using the state-of-the-art infrastructure and technologies needed, so that there will be easier access to using and obtaining accurate testing results. In this paper, first, we summarize three aspects of the heterogeneous information-centric wireless sensor networks' test bed, including its requirements, testing technologies, and performance evaluation; second, we describe the heterogeneity of the test bed from three perspectives, including hardware resources, software resources, and communication technologies; third, we analyze the composition and implementation of each recent representative heterogeneous test bed in detail and the adequate compactness and the satisfactions of the requirements with each other; finally, we point out the open research issues on heterogeneous test bed. We found that the current development of information-centric wireless sensor networks is full of challenges.

INDEX TERMS Wireless sensor networks (WSNs), Internet of Things (IoT), testing platform, heterogeneity.

I. INTRODUCTION

Wireless Sensor Networks (WSNs) [1], [2] are a kind of distributed sensor network and an important technical form of the underlying network of the IoT. With the rapid development of network technology, the network is facing more complex problems. WSNs [3] are data-centric and closely related to the information-centric of the Internet [4]. Therefore, it is necessary to learn from the information-centric network architecture and study the technology of wireless sensor networks. In the early stage of WSNs research, owing to lack of testing tools and a large number of available nodes, the feasibility of algorithms, protocols and applications, which is mainly based on the theoretical analysis have been verified and evaluated. Due to the high computational complexity of the structure of the mathematical models, much simplification need to be done to solve practical problems in the application of these models, which can reduce the reliability of theoretical performance analysis. After that, all kinds of operation systems and simulation tools are suitable for WSNs to make simulation and physical testing possible.

TABLE 1. **Requirements of HWSNTB.**

Perspective	Requirements
Test bed	Heterogeneity Scalability Portability Federation
Node platform	Flexibility Mobility
User	Interactivity Debuggability
Experiment	Repeatability Concurrency

However, the WSNs application environment is complex and variable, and the wireless channel is easily disturbed [5], which means it is difficult for simulation testing to get the evaluation results of high reliability and high trustworthiness. Through the establishment of network testing platform based on sensor nodes, the protocol and algorithm of testing network can be verified during the actual application process. It not only contains all factors that affect the network state comprehensively, but also avoids the theoretical errors caused by the model simplification [6], [7]. Based on the mentioned above, it provides a basis for the study of information-centric WSNs which are different from data-centric traditional WSNs. Therefore, people are increasingly concerned about the platform of testing technology of wireless sensor networks [8].

In recent years, micro sensor [9], wireless communication [10], [11], computing and other related technologies have experienced rapid development. The software and hardware resources and protocol elements in WSNs applications are increasingly expanding. To meet the heterogeneous characteristics of the actual prospect, we need to propose more comprehensive testing requirements for the testing platform. Testing technology and performance evaluation are core elements of the testing platform, and they are also facing enormous challenges. In order to conduct more flexible and precise tests [12], these two aspects still entail constant improvements and perfection.

This paper mainly discusses the Heterogeneous Wireless Sensor Networks Test Beds (HWSNTB) testing platform which is information-centric, and summarizes the related testing requirements, testing technologies and the performance evaluation. Explaining the relationship between WSNs and information-centric IoT (IC-IoT) is expounded from technical level. Based on the existing testing platform, the heterogeneity of the mining platform is analyzed. The several aspects are previously explained in detail with the specific testing platform and the applicability of different platforms is put forward. Finally, the performance characteristics of the heterogeneous testing platform and the conformity of the testing requirements are compared, and some related problems are pointed out for future research. The challenges faced by information-centric WSNs are summarized, and a new idea of WSNs development is put forward.

II. AN OVERVIEW OF HWSNTB

This part of the paper is organized as follows. In section A, some testing requirements are given. In section B, we present different testing technologies to adapt to different standardization organizations. In section C, we conclude the importance of network performance and identify HWSNTB to our work.

A. TEST REQUIREMENTS

In general, the design and construction of the testing platform are mainly based on specific testing purpose for completing the expected testing tasks. Different testing purposes have different testing requirements, such as the repeatability of the testing bias experiment for the algorithm, the interaction between the testing bias of the application and the platform. With the in-depth research of WSNs, the reduction of node cost and the integration of various communication technologies are difficult, because of the complex heterogeneous platform. In order to achieve the desired results, we summarized the related requirements of the heterogeneous testing platform, which contains four layers, including platform, node, user and experiment, as shown in Table 1 [13].

1) PLATFORM LEVEL

Heterogeneity: It contains multiple types of nodes and devices, supporting multiple types of interfaces, operating systems and network protocols.

Extensibility: Different experiments need to adapt to different network sizes, topologies and node densities. The failure of the nodes or addition of the new nodes will result in the changes in network topology. So it is of vital importance to have extensibility.

Transferability: To achieve better reuse of the resources, the platform should be able to use different experimental environments, not only through comparing, but also reducing the cost of deployment.

Combination: When multiple independent testing platforms are managed in a unified way, the sharing of the resources can be realized, and a large-scale testing task can be completed, and more sample testing methods are provided for the users.

2) NODE LEVEL

Flexibility: The node structure is flexible and free to control, supporting the customized impolder of MAC layer, network layer and application layer, so that it can be tested at the multiple network levels.

Mobility: When performing some outdoor monitoring tasks, the deployment scope of the nodes is wider. By using the mobile nodes, it can reduce the number of nodes and improve the data transmission efficiency [14].

3) USER LEVEL

Interactivity: Users can freely interact with nodes and servers, deploy or view experimental information through web interface or other access routes, and conduct comprehensive regulatory control over the experimental process.

4) EXPERIMENTAL LEVEL

Debugging: The effective real-time transmission and storage of testing data are the basis of ensuring the debugging of the testing platform. During the running of the testing platform, it is crucial to output text status information and related registers, variables in real time, and related information needs to be saved in the database for post-mortem analysis.

Reproducibility: In many cases, the same experiment needs to be repeated in same environment to obtain the accurate testing results [7]. For example, when testing a certain parameter, a more accurate conclusion can be obtained by comparing the results of different parameter values. Using reproducibility can quickly build your own experiments on the basis of the predecessors and speed up the research process.

Concurrency: For some large-scale testing platforms, concurrent operations that support multiple users and multiple experiments can maximize resource utilization and save experimental time. Since the platform has been virtualized [15], it can better support experimental concurrent operations.

B. TESTING TECHNOLOGY

Due to the differences in protocols or standards of the products formulated by different standardization organizations, and for the lack of authoritative and complete common standards, the related tests have become extremely difficult. In order to unify testing standards as soon as possible, the Standards Working Group on Sensor Network (WGSN) has set up a testing specification project group (PG11) to conduct research and promote development of the sensor network testing standard system. According to the sensor network standard system framework put forward by WGSN, the testing part includes the following three aspects:

1) Conformance test. It is used to detect the functions of certain sensors such as RFID tags, network gateways, and smart terminals in the sensor network to meet the standards and determine the degree of consistency between the measured object's implementation and the standard. It mainly includes RF consistency and protocol conformance testing.

2) Interoperability test. It is used to verify whether the tested network device has all the functions that the user needs. And the interoperability test of the entire network is completed by observing the interaction process between the device under testing and the standard device on the network interface.

3) System test. It is responsible for testing the performance, security, and functionality of the entire network to determine whether each module can meet the user-related business requirements in actual applications, and also to identify the possible points of failure and insecurity, and thus it can improve system availability.

Wireless sensor networks testing technology is of great significance for the development, operation, and maintenance of network systems. On the one hand, it helps analyze network behaviors, locate network failures or bottlenecks, and optimize network operations. On the other hand, it helps evaluate network performance, understand network operation patterns, and plan network deployment [16]. It is instructive to develop related technologies [17]. The following tests are for different purposes and some existing testing techniques are introduced.

1) When tested IPv6-based WSNs protocol conformance, the author in this paper [18] selects a series of such measurement instruments as WSNs multi-node simulators, gateway simulators, vector signal generators and analyzers, power meters, data acquisition analyzers and conformance testing instrumentation with them serving as testing tools, to build a verification platform for testing.

2) When we test protocol conformance and interoperability, we need to take into account the heterogeneity, dynamics, and diversity of application of sensor networks. Author in this paper [19] proposes a unified testing architecture for testing managers and agents. The testing agent is used to match different protocols and physical interfaces. It can work independently, and can be completed by multiple testing agents. And the testing manager makes a centralized management of the testing agent and configures different testing applications. This standard provides a unified testing case for WIA-PA, 6LowPAN, and ISA100.11A [20]. The specific testing system is shown in Figure 1.

3) To evaluate and test the feasibility of a sensor network middleware design method, and also verify whether the service provided is efficient and reliable, the author in this paper [21] combines the ISO/IEC 9126 standards and the characteristics of the sensing network application, maps the former to the latter and finds the similar parts of them, and proposes the testing standard for the sensor network middleware and the content of the testing.

4) When testing the performance and security of routing protocols for wireless multi-hop networks, based on the routing algebra and unified routing model, the author in this paper [22] achieved the comprehensive testing of multiple protocols. The protocol rule, parameter, test and analysis

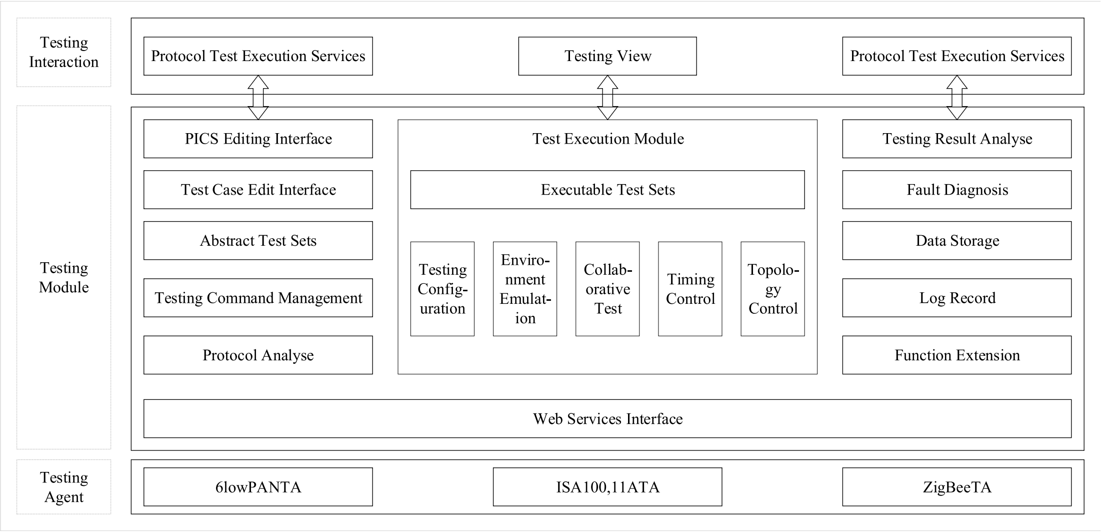

FIGURE 1. Unified testing system of 6LowPAN, WIA-PA and ISA100.11A based on Web.

libraries are designed by modularization architecture, and the tests are carried out with different testing methods, scalability, and compatibility. What is more important is to realize the automation of operation analysis and reduce human error. Figure 2 shows the structure diagram of the testing core processing module of the platform.

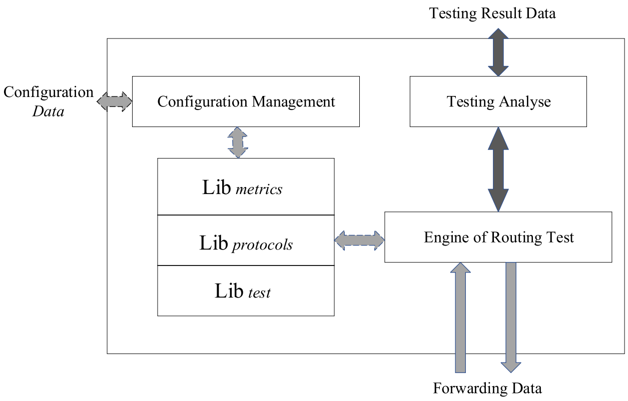

FIGURE 2. The structure of core testing processing module.

It separates the configuration data, testing result data, and forwarding data, and effectively avoids the interference of other data streams to the testing process.

5) On testing the platform performance, the author in this paper [23] develops a wireless sensor networks experiment bed, JmoteNet, which can carry out mirror download, node programming and testing data collection [7], [24] through the back end wired control network, and it uses the lightweight measurement module embedded in the node to efficiently obtain the performance parameters of power, throughput, delay, packet loss rate, and network topology.

6) For the testing reliability and fault tolerance of WSNs, Huang [25] adopts the testing technology of fault injection (FI). This technology is based on a specific fault model, artificially and consciously generating faults and applying them to the system testing. The purpose is to accelerate failures of system, occurrence of failures, and also observe and receive feedbacks of the system's response information to the injected failures, equally to validate and evaluate the system through analysis.

7) In order to realize the zero interference of the test, Zhao *et al.* [26] designed a high precision testing rear panel, using the internal interception technology (using the testing rear panel to capture the interconnect signals of the sensor nodes directly) and the extra transmission network to achieve the transparent test of the high precision of WSNs during operation, which can conduct signal analysis, protocol verification and evaluate the performance of WSNs accurately. Figure 3 shows the relevant modules for the interaction between the platform remote client and the testing server. Results show that the remote access client includes multiple groups of testing applications, such as event replay and performance evaluation. According to specific needs, these testing applications use the subscription mechanism to access the testing data on the testing server through the existing network, and then analyze and process it. According to the summary, it can be seen that most of the existing testing technologies are not universal because of the influence of the characteristics of WSNs itself, even based on the edge computing [27], [28]. Therefore, there is still much room available for the study of universal testing models. In order to have a clearer understanding of the testing technology, the related technologies mentioned above are summarized in Table 2.

C. PERFORMANCE EVALUATION

Like traditional networks, information-centric WSNs also need to provide quality of service (QoS) for different users

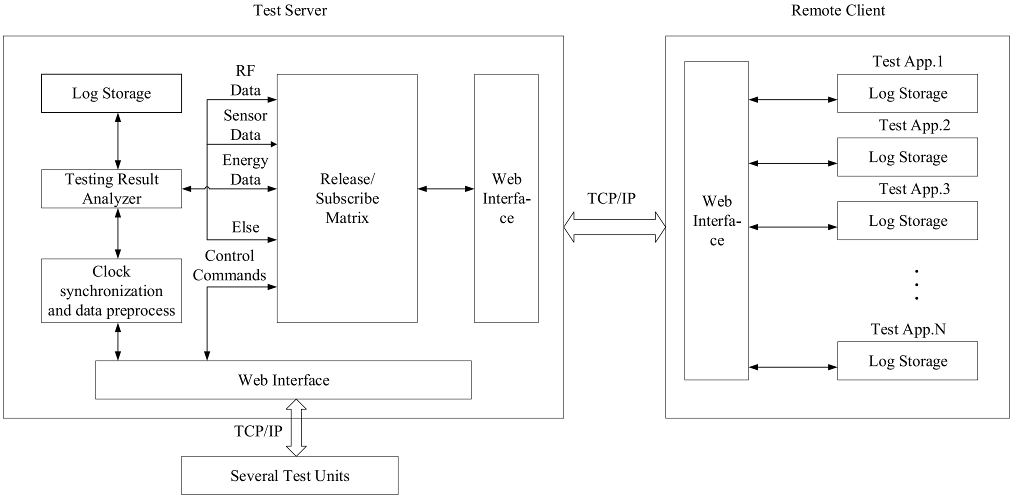

FIGURE 3. Block diagram of test server and remote access client in testing platform for WSN.

TABLE 2. Summary of some specific testing technologies.

Testing Purpose	Testing Technologies
Protocol conformance test	Use conformance testing instruments
	Unified testing system based on testing managements and test agents
Middleware test	Mapping the ISO/IEC 9126 standards to the middleware testing standards
Performance test	Based on routing algebra and the unified routing model;
	Protocol rule library, parameter library and testing and analysis library
	Rapid program deployment through ControlNet; Based on extended hardware and built-in performance measurement Non-Intrusive backplane-based and sniff-inside
Reliability and fault tolerance	Based on fault injection

and applications. The differences are the node resources, communication capabilities, and processing capabilities. In the WSNs, they are extremely limited, and the maximum effort can only be made to balance the performance in all aspects. With the expansion of the application field of WSN, many applications have put forward higher requirements for QoS, such as multimedia applications and real-time monitoring systems [29]. So qualitative evaluation or quantitative research of their performance are of great importance. For applications, the focus is on coverage, measurement accuracy [30], and the optimum number of active nodes. For the network, the main indices are commonly used end-to-end delay, packet loss rate, bandwidth, and throughput. Wen *et al.* [31] systematized it and found the intrinsic relationship, which provides a theoretical reference for analysis and design for QoS guarantee and cross-layer optimization in specific network applications. Figure 4 shows the WSNs hierarchical QoS indicator.

Whether it is the testing of various physical parameters or algorithms, protocols, and related functions and performance of different applications, it is necessary to select appropriate performance indicators and testing results for comparison and analysis, which can determine whether to meet the testing requirements. Usually, we choose higher correlation, more commonly used or typical parameters and the accuracy of the results obtained by different evaluation methods are different, usually decided by the accepted values of the parameters or the comparison with the actual situation to get the final conclusion. Wu *et al.* [32] used the modeling mechanism based on Performance Evaluation Process Algebra (PEPA) to analyze and evaluate the network throughput, utilization rate and response time. PEPA has a compositional description technology that can describe a system model as a set of processes that interact through execution actions to evaluate whether a process is performing correctly and timely.

In order to accurately evaluate the overall network performance, Wang and Wang [33] proposed a performance evaluation method based on energy efficiency and delay for WSNs. Firstly, the influence of channel error rate, packet retransmission mechanism and collision rate on network performance are analyzed comprehensively. Then two evaluation indexes of network energy efficiency and delay are constructed, and

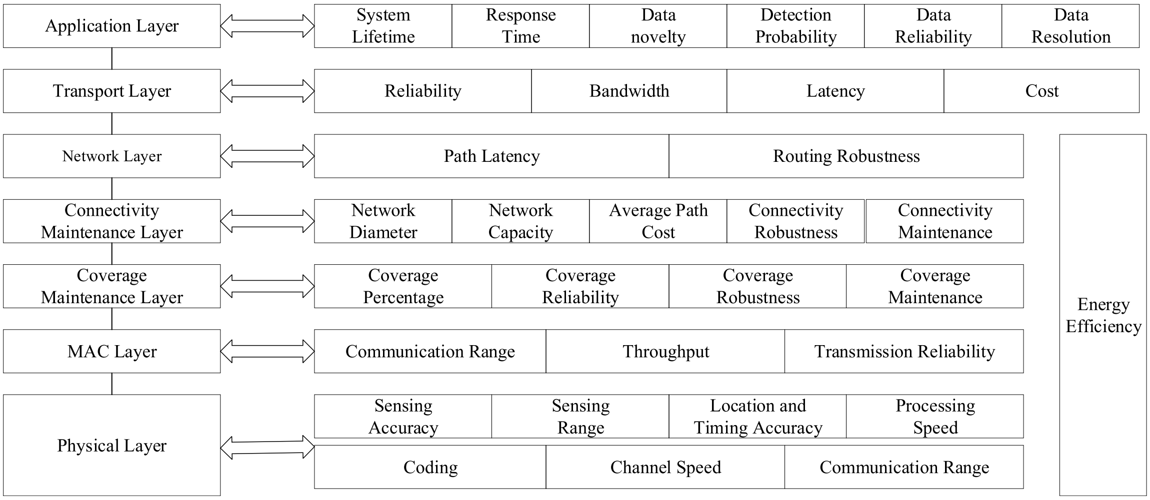

FIGURE 4. QoS parameters in WSNs layers.

are weighted by entropy method. The neural network with strong nonlinear approximation capability is used to establish a network performance evaluation model. Then the influence of various factors on network performance is analyzed under different packet length conditions.

In summary, HWSNTB is crucial to meet the needs of complex and multivariate testing and promote the research of WSNs in practicability and related technology. And, it is imperative to study cross platform, multi-technology integration, large-scale and feasible heterogeneous wireless sensor networks testing platform. At present, scholars at home and abroad mainly focus on mobile [34], [35], different platform research and development and system architecture [36], but the research on platform heterogeneity is not in-depth. The heterogeneous testing platform can accomplish a variety of testing tasks and realize resources reuse and sharing, and reduce the deployment overhead in essence. Therefore, in our work, we will analyze the heterogeneity of the platform in detail.

III. COMPOSITION OF HWSNTB

Figure 5 shows the structure of the general WSNs testing platform, which consists of three parts: the area to be tested by sensor nodes, the communication facilities for data transmission and the server required for testing. Sensor nodes transmit perceived data to the server by wireless communication and local or remote users access the server or nodes to obtain destination information. Through analyzing the whole process, the source of platform heterogeneity can be explored further.

First of all, there are many parameters in the area that needs to be measured. With the rise of smart home, an increasing number of mobile devices are added to WSNs as a part of the sensing devices. Therefore, the node is heterogeneous. Secondly, most of the testing platforms are designed for specific purposes, and the software resources used will be selected according to the corresponding testing requirements. So there will be differences between the platforms in this respect. Finally, due to many open communication protocol standards, different platforms and even the same platform may use a variety of communication technologies, such as ZigBee, IEEE802.11. In the early research of WSNs heterogeneity, the emphasis is on node level, such as computing power heterogeneity, link heterogeneity and energy heterogeneity. With an increasing number of heterogeneous elements in the platform, it is necessary to obtain more comprehensive analysis and summary, and this paper will study the heterogeneity of the testing platform from three aspects: hardware resources, software resources and communication technology.

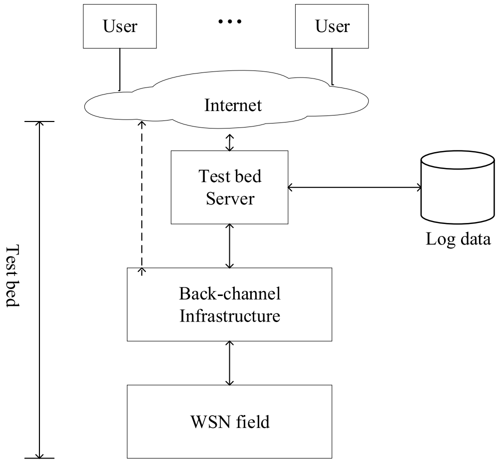

FIGURE 5. Generic building blocks of a WSN test bed.

A. HETEROGENEITY OF HARDWARE RESOURCE

In the structure of the whole testing platform, there are two kinds of hardware resources involved: one is sensor node, the other is facility, such as PC, mobile portable device, USB hub, AP (Access Point), gateway and adapter.

TABLE 3. Summary of features of sensor node platforms.

Platform	Integrated Sensor	MPU	Bit	RAM/KB	Support OS
MicaZ [37]	No	ATmega128L	8	4	MoteWorks
TelosB [38]	Yes	MSP430F1611	16	10	TinyOS
EyesIFX v2 [39]	Yes	MSP430F1611	16	10	TinyOS
Tmote Sky [40]	Yes	MSP430F1611	16	10	TinyOS
Sunspot [41]	Yes	ARM 920T	32	512	TinyOS, Linux
Imote2 [42]	Yes	XScale PXA271	32	256KBSRAM 32MBSDRAM	TinyOS, Linux, SOS
Stargate [43]	Yes	XScale PXA255, SA-1111 StrongARM	32	64MBSDRAM	Linux
Platform	Communication	Freq. Band	Data Rate/Mbps	Radio	Power
MicaZ	ZigBee	2.4GHz	0.25	CC2420	2AA
TelosB	ZigBee	2.4GHz	0.25	CC2420	2AA, USB
EyesIFX v2	USB	868MHz	0.064	TDA5250	1AA, USB
Tmote Sky	ZigBee	2.4GHz	0.25, 0.04,0.02	CC2420	2AA, USB
Sunspot	ZigBee, 6LoWPAN	2.4GHz	0.25	CC2420	3AA
Imote2	ZigBee	2.4GHz	0.25	CC2420	Batteries, USB
Stargate	ZigBee, IEEE802.11a/b	2.4GHz, 5.2GHz	0.25, 54, 11	CC2420	Batteries, USB

Different testing platforms have different numbers and types of hardware resources.

As an important carrier of data perception, sensor nodes need to be able to independently complete the collection and the processing of various parameters in the physical world. The low-level nodes are only responsible for the acquisition of data. So it is necessary to meet the characteristics of low power consumption, long working hours, and large memory for the gateway nodes have to meet the characteristics of high computing power, high processing speed and wide communication range. Energy supply modules mainly consider whether to obtain energy from the outside world, build a built-in energy consumption measurement module to regulate energy consumption and configure a variety of energy saving modes (such as dormancy, Power-aware). Potdar *et al.* [44] compared the specific nodes with the parameters required for the target application, including the key technologies and communication technologies used in the design, such as antenna design, module components, storage, power, security [45], remote programming and interfaces. In addition, Farooq [46] also introduced multimedia nodes, including Mesh Eyeen and WiCa. Table 3 selects the commonly used nodes in the testing platform to sum up the related parameters. It can be seen that most of these nodes have a single structure and the techniques used are very similar. Thus to make the node more flexible and meet the diversified requirements, Kouche [47] also improved the structure by comparing the existing technology of node processor and communication module to realize the node sprout, and provide valuable reference for the design of nodes.

B. HETEROGENEITY OF SOFTWARE RESOURCES

The construction of the testing platform cannot be built without the support of various software resources. In general, software resources need to complete the execution and monitoring of the testing task and management and distribution of resources through the cooperation of different functional modules on the related hardware platform. It is divided into operating system, middleware and server. In fact, the server is the combination of software and hardware, but it is classified as software resource, because it mainly acts as the role of providing service and managing storage resources in the testing platform.

The operating system (OS) includes Windows and Linux on PC, as well as OS for WSNs. Due to the unique nature of WSNs and the resource limitation of nodes, it is necessary to design a new type of operating system for WSNs, which can support node processor, memory, peripheral communication interface, energy and a variety of specific upper layer applications. At present, TinyOS [48], SOS [49], Contiki [50] and Mantis [51] are more common.

Middleware, as the system software between the operating system and the application program, provides a unified running platform and friendly development environment by shielding the heterogeneity of the underlying components. It narrows the gap between the application and the underlying equipment, and solves the interoperability problem of the application cross platform. The main role it plays is to support node programming and provide support of service quality, data management, resource management, remote communication with nodes and control the topology of WSNs and provide security protection. More importantly, it can provide

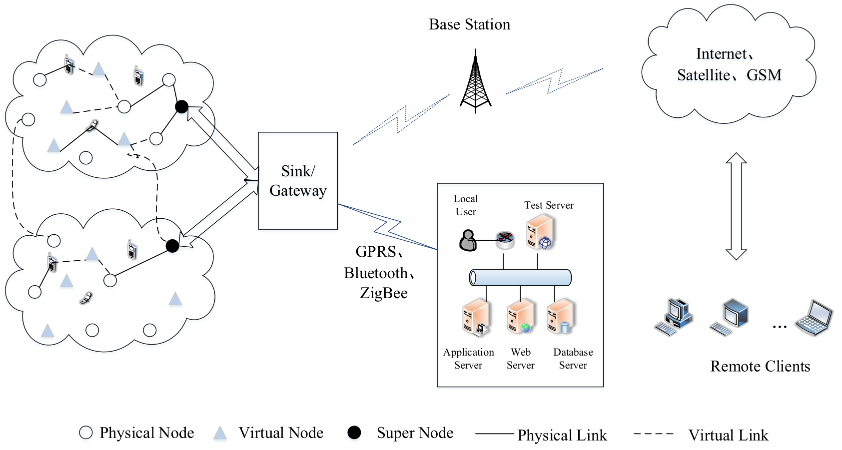

FIGURE 6. Structure of heterogeneous wireless sensor networks test bed.

a variety of mechanisms such as effective interaction between tasks and networks, task decomposition, cooperative work among nodes and heterogeneous abstraction. But a dozen kinds of middleware can only support the heterogeneity of the platform in theory. So there is still a lack of support for heterogeneity. And, we need to study in depth [52].

C. HETEROGENEITY OF COMMUNICATION TECHNOLOGY

In the whole testing platform, the communication technology that needs to be used includes short distance communication and remote communication. Considering the heterogeneity of the devices, the relatively common design is that communication between nodes within the area under testing uses short-range wireless communication technologies such as ZigBee based on IEEE802.15.4 protocol, 6LoWPAN, RFID and Bluetooth, for example, between ordinary nodes and ordinary nodes, between the ordinary node and the advanced node. Converging nodes and servers, users and server, or node communication entails remote communication technology, such as Ethernet. The sensor module of the node communicates with the wireless communication module through the interface protocol. There are some commonly used I2C and ADC/DAC conversion protocols. In addition, there is more commonly used Power Over Ethernet (POE), which can transmit power and data in the cable at the same time, and solve the problem of the energy supply of the node.

For the sake of enlarging the scale of the testing platform and maximizing the utilization of resources, the VTBs proposed in this article (virtual test beds) is the prototype of WiseBED [53], which can arbitrarily change the number of physical nodes, simulation nodes and the number of actual links and virtual links in the platform, thus changing the topology of the network and making the platform testing more flexible. IWSN (a web service interface) is used to provide the Web service interface for the unified management and access of the mixed platform, enabling users to access and control any node.

After a detailed summary of the heterogeneous elements of the platform, the system structure diagram is shown in Figure 6. The system structure is presented to show it in a clearer and more intuitive manner. The diagram basically covers all the heterogeneous categories discussed previously, such as the common nodes in the nodes, mobile devices, virtual nodes and gateway nodes. A type of communication technologies and servers are used to meet the different needs of local and remote users.

IV. ANALYSIS OF HWSNTB

Through heterogeneous classification, it can be clearly recognized that in the platform design each link may need to deal with many problems caused by heterogeneity. How to choose complex and different functions of hardware and software resources and communication technology to make the overall structure, meet the expected requirements and obtain the best testing results still require further study. The following is a detailed introduction to the above mentioned aspects of the heterogeneous wireless sensor networks testing platform, focusing on the platform used in testing technology and performance evaluation. The details of selecting some more typical testing platforms and using the most prominent features of the platform to classify them are shown in Figure 7.

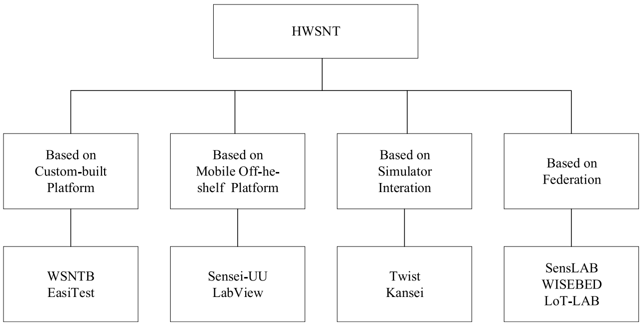

FIGURE 7. Classification of HWSNTB.

A. HETEROGENEOUS TESTING PLATFORM BASED ON SELF-MADE NODES

This kind of testing platform makes use of self-made sensor nodes to conduct the experiment. Each kind of function can be customized according to the demand, which increases the autonomy and diversity of the test. The nodes are used by researchers in the laboratory to test the results, not yet commercialized. Consequently, the scope of application is limited. Relatively speaking, the platform is small, which is deployed in the laboratory and used in a small range of testing, but it also has a certain degree of scalability.

1) WSNTB

WSNTB [54] is a reconfigurable heterogeneous sensor network testing platform developed by National Tsinghua University of Taiwan. WSNTB is composed of server layer, gateway layer and node layer.

Using self-made nodes Octopus I and Octopus II can support ZigBee protocol communication. They connect Ethernet through USB or RS232 interface and run TinyOS and self-developed operating system LOSs, and develop middleware to facilitate user processing experiment. The platform provides two access routes:

1) local mode that allows users to select specific nodes locally to cater for their needs. When the user starts the experiment, he is reminded to add a remote sequence port, and then transmits data directly through this port;

2) carrying out related operations through the web side. The platform includes 2 WSNs and 3 gateways. The users are free to choose the configuration. Net4501 and net4801 single board computers are used as gateways and ZyXEL ES-108A Ethernet gateway as LAN gateway. VIPs can use high priority bandwidth.

The software structure includes service interface layer, testing platform core layer and resource access layer. To ensure security, private IP addresses are used to communicate with the database. In addition, it also contains an event reminder module to ensure accurate and real-time control of the experimental process. Simulation server is extremely essential to local mode and real time control protocol. Microsoft VB and Java run-time library are installed to support TinyOS and Cygwin environment. Virtual com software (creating virtual port) is used for local mode. In order to enable the node to restart automatically, each node is bound up with the hardware reset device.

The node has its own energy consumption measurement module, and the platform verifies the protocol and algorithm on the visualization software by collecting data [55].

2) EasiTest

EasiTest [56] is a multi-radio heterogeneous wireless sensor networks testing platform, consisting of testing network part and integrated monitoring part. The previous one is composed of self-made EZ271 and EZ521 nodes, wired and wireless gateways, and the latter one is system management server that consists of database server and Web server. EZ271 which can support ZigBeeP / 802.15.4 communication protocol and download TinyOS operating system, and can also run embedded Linux operating system, has the characteristics of medium speed and multi-radio. As a WiFi transmission module, G2M5477 can modify the protocol and configure the parameters of WiFi network. EZ521 is a low-speed node with a structure similar to that of EZ271 that can realize remote programming of EZ521 nodes through WiFi network. The platform makes use of the function of node multi-radio to compare the link throughput index and verifies that the multi-channel transmission can increase the data transmission rate by nearly two times. The developed visual control management software facilitates users to configure and supervise different types of experimental tasks.

B. MOBILE HETEROGENEOUS TESTING PLATFORM BASED ON COMMERCIAL PRODUCTS

This kind of testing platform uses the existing commercial products to deploy and has strong portability. Due to the maturity of the software and hardware used, the testing risk is reduced, and the platform can be applied to different experimental environments. The addition of mobile nodes improves the flexibility of testing. However, the function of the product is limited and it can only achieve the desired testing effect by adding different hardware, and need to consider the differences and compatibility between the products.

1) LabVIEW

LabVIEW [57] is widely used to simplify the deployment and design and it is beneficial to the reuse of resources and the migration of the platform, which adopts the existing hardware and LabVIEW software package. The user interface and system management tools are developed under LabVIEW programming environment to provide a high level network view to users. The interface program is installed on the management PC. Once the node is programmed separately through RS-232 interface, the LabVIEW application program will record and visualize the testing data in real time. The platform consists of two independent networks, each connected to the base station node of PC through serial port. In the first network, 15 MicaZ nodes are configured to receive data in a multi-hop mode, and the second one is configured with 8 Cricket nodes that communicate with the base station in a single hop mode. Four of the MicaZ nodes are installed on Arconame robots or Cybermotion sentry robots that provide mobile control. The initial position of the robot is known. Cricket nodes have ultrasonic positioning modules that measure the relative positions between nodes. Two of them were carried on people to track their locations. The wireless communication between robot and MicaZ node is at 433MHz frequency. LabVIEW interface allows the installation of TinyOS program to node programming, and provides GUI for visual analysis of runtime data. For mobile nodes [58], a library function for sending commands and receiving data is established. If a new node is added to the robot or a new location algorithm is completed on it, the corresponding library functions will be updated synchronously.

The platform has carried out two experiments to verify the precise location of nodes and to adapt to the variability of network topology. A dynamic model is proposed to evaluate the absolute and relative positions of nodes. The strategy of matrix-based Discrete Event Control is used to deal with the problems of node mobility, adding or deleting, and network failure caused by poor communication connection.

C. HETEROGENEOUS TESTING PLATFORM BASED ON SIMULATION

This kind of testing platform mainly uses simulation software and it can provide more flexible and diverse testing methods, but there may be some problems in time synchronization and experimental control.

1) TWIST

TWIST [59] is a scalable, reconfigurable indoor testing platform developed by Berlin University of Technology, spanning three floors of office buildings and deploying more than 100 nodes. It is mainly composed of testing node, gateway node, USB hub and cable, testing server and control center. There are two types of nodes: Telos and eyesIFX v2. The gateway node (super node) is a customized operating system. By sending USB control information, the corresponding software can control the energy supply of the given port node of the hub and the state transition between USB power supply and battery power supply. PostqreSQL server is used to store application and debug data. The PostGIS extension on it supports experiments based on location-based services. The platform uses special hardware socket. It has unique identifier and fixed geographical location. The USB interface of gateway node can detect whether the node is plugged in socket, and locate the node by matching the corresponding node IDs in the database. Through using Cooja-TWIST plug-in, the platform can be used directly through Cooja simulator, and the network topology can be dynamically modified by event simulation such as node energy depletion or adding new nodes. In order to realize the parallel programming of nodes, the control center establishes separate threads for each gateway node, and each thread executes Python scripts on the gateway node by remote SSH command and in turn creates threads for connected nodes. The platform can make use of different node densities, network sizes and node dynamics to carry out related experiments. For example, when testing routing protocol rain, the throughput on the link can be measured by controlling the number of working nodes. You can also read the USB interface information to measure the energy consumption of the node.

2) Kansei

Kansei [60] is a comprehensive testing platform developed by Ohio State University, including static node arrays, portable node arrays, removable node arrays and Director software platform for remote access control. The static node array consists of 210 nodes running TinyOS. XSM (extreme scale Motes) is connected to the gateway node XSS (extreme scale arguments) via a dedicated 51 pin connector which connects PCs clusters via Ethernet. One PC is used as the main server control node and remote access, while the other PCs are used for visual data analysis, simulation diagnosis and analysis. It is combined with one or more portable node arrays to record data and regional testing. Each portable Trio node contains specific sensors and common software services such as data storage compression [61] and time synchronization management. The mobile node consists of five Acroname robot nodes. The Stargate nodes on the nodes communicate with the nodes in the static array using 802.11b. The portable network is used to deploy to the actual environment for data acquisition, and the collected data is sent to director, a unified software platform, via Ethernet. In order to realize the simulation, the components of the analog communication and perception function on the TOSSIM are replaced by the components dealing with the interaction with the nodes, and the mapping relation is used to connect the virtual node and the physical node. The different virtual nodes can be mapped to the same physical nodes, and the simulation time is used as the standard of time synchronization. When a real event is executed, the simulation time parameters of the event are recorded, the current simulation behavior is stopped and the parameters are converted to the real event time, the time parameters are collected after the execution, and then the time is returned to the emulator. And the artificial data are generated by probabilistic model. The experimental environment can be restored by event injection, which can accurately repeat the experiment.

The platform has carried on the experiment to the application related to the route and has selected 5 or 13 actual nodes and some other simulation nodes separately to carry on the comparison. The result shows that when the actual number of nodes increases, the route transmission path that can be used for simulation also becomes longer. Kansei is a currently part of a large project called Global Environment for Network Innovation (GENI), designed to test large-scale federated platforms.

D. HETEROGENEOUS TESTING PLATFORM BASED ON CROSS-REGION ASSOCIATION

This kind of testing platform belongs to the large-scale test platform which is a cross-region joint testing platform. All kinds of resources are abundant, and there are no restrictions on node type, operating system, time and place of experiment. Users can configure experiments arbitrarily through registered accounts, which is quick and convenient. But the scale is too large and the management is relatively difficult. Furthermore, the security also needs to be strengthened.

1) SensLAB

SensLAB [62], is a large scale testing platform with more than 1000 nodes deployed at more than 4 sites in France. The platform mainly provides a precise, open and

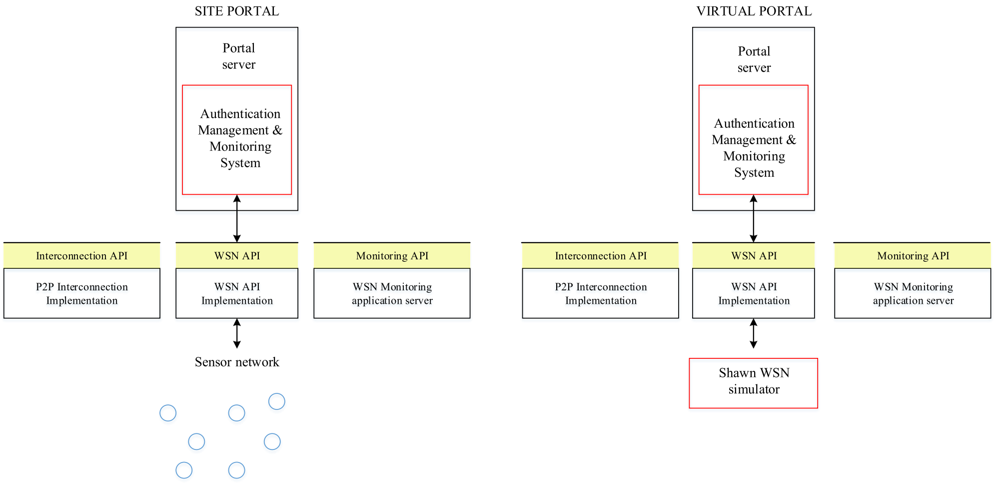

FIGURE 8. Software aspects of WISEBED.

multi-user accessible scientific tool to support the design of large-scale practical applications, R & D, commissioning and verification. Two of the sites support access to mobile nodes (with the aid of electronic toy trains), allowing users to deploy their applications via Web access, with no restrictions on programming languages, programming models and OS.

The SensLAB node consists of two open nodes, WSN430 and a gateway motherboard, which are based on a low power MSP430 processor, a fully functional ISM wireless interface (IEEE 802.15.4/ 2.4GHz) and some sensors (sound, light, temperature). One of the WSN430 nodes controls the other open nodes accessed by the user. The gateway motherboard is used to control and connect the two nodes. The main functions are automatically deploying the firmware of the open node and accurately monitoring its energy. Wireless environment monitoring (RSSI measurement and noise injection) and connecting Ethernet communicate with Node Handler and support Poe energy management via Gigi connection module or mobile WiFi. The platform software architecture includes control node software, gateway node software, experimental processing software, batch scheduling software, user virtual machine and server system framework. The virtual machine provides command-line client program, interacts with nodes, connects with experimental processing software, and performs firmware update on any node.

The platform uses 255 received nodes and one sending node to verify the packet loss rate, and obtains the adjacent matrix of RSSI information in the wireless link between each two nodes. The results show that when the RSSI is greater than -65dBmPer > 0.9, the probability of each packet being received is the highest, and when the RSSI is less than -70dBmPe 1-PER, the probability of packet loss is very high. Then the RSSI parameter value is reorganized by community discovery algorithm, which shows the number, size and organization of the deployment node cluster.

2) WISEBED

WISEBED [53], similar to SensLAB, consists of 9 separate testing platforms which are combined based on the concepts of platform virtualization and virtual links in different regions in Europe. The platform is deployed with 550 nodes, such as still nodes likes iSenseo, TelosBor, MicaZTMote Sky and mobile nodes likes Roomba Robot530, SunSpot, Spot-Moway. These nodes have a variety of sensors and wireless chips, such as CC2420 (2.4GHz) and CC1100 (868MHz). The backbone network includes the wired and the wireless (Ethernet, IEEE 802.15.4, WiFi). The system structure is based on hierarchical structure and each layer is composed of one or more brother testing platforms which is mainly responsible for responding to different event commands and communicating with other platforms. The lowest layer is the node device running on iSense, Contiki and TinyOS. Figure 8 is a software configuration diagram of a platform. Each independent platform is controlled by a port server. And port servers in different geographical platforms are connected by overlay network. The coverage node has the same interface as the port server. And the user can access the unified distributed testing platform through the connection overlay network. The single platform can be accessed through the port server. The services provided by inner layer of the port server include providing gateway access nodes (IEEE802.15.4, RS232), connecting local storage devices (XML files, RDBMS) to store debug history and access lists. The outer layer provides user services to manipulate the platform and access port servers with a common IP interface. The platform uses TARWIS [63] management system to manage resources, and provide multi-user access, online configuration and scheduling experiments, automatic data query and real-time monitoring. The system is independent of node type and OS. Web services provide authentication for the platform, authorization (using the famous distributed registration system Shibboleth), user management, network control debugging and configuration

(WSNs API). Each entity in the network has unique identification (using URN).

As a virtual testing platform, the Shawn simulator communicates through virtual links. The messages sent by the nodes are transmitted to the local port server of the testing platform through routing, and the server is compared with the description of the virtual testing platform to judge the adjacent nodes. At the same time, it checks the possibility of LQI computing to lose or change parts of the message, and then transmits it to the target node through the form of message.

Wiselib is a special platform general algorithm library. It provides general API implementation algorithms and can be compiled on different software and hardware platforms. The algorithm is written in C++ and supports a wide range of platforms and OSs.

3) IoT-LAB

IOC-LAB [64] is suitable for the testing of a wide range of IoT applications. It is the logical evolution platform of Sensor LAB and has deployed a large number of nodes and mobile robots. And these nodes are distributed into 6 different sites in France. IoT-lab nodes are interconnected through the backbone network which provides energy and connects them to the server. The management software provides real-time access to the nodes. An IOC-LAB node consists of three modules: Open Node (ON), Gate Way (GW) and Control Node (CN). ON is a low power device reprogrammed by users. GW is a small Linux computer. CN is used to control ON and monitor its energy consumption. The platform consists of static nodes such as WSN430, M3, A8 and dynamic nodes such as Turtlebot, WiFibot. Robots can use infrared beams and cameras to find the docking point for charging.

The nodes in the platform can support five kinds of OS: FreeRTOS, Contiki, TinyOS, Riot and Open WSNs. By controlling CN, users can select configuration to monitor the frequency and the number of measurements, activate the radio frequency monitoring mode and control the receiving and forwarding of the node data packets. Meanwhile, using the open source measurement function library to collect data and compressing the data by using ZEP protocol can also be executed. The GW module provides a REST-based management interface to implement all API instructions. GW connects to ON's JTAG port to run Open OCD GDB server, which enables users to debug nodes remotely. The robot runs Ros Linux that contains the same management interface. It can locate itself by calculating the number of wheel rotation and record position information by using OML format, and synchronize it to the back-end software through WiFi. The platform connected by VPN has one main site and six sub-sites. The main site is responsible for user authentication (LDAP directory tree) and private domain name server (DNS) system, and interacts with the open source resource management software OAR. The operating system platform uses the register manager to manage authorization, users and resources. Users can deploy their experiments on the IOC-LAB website after registering their accounts. They can directly use CLI tools to edit source code, install firmware for nodes, visit the serial ports of nodes, record A8 nodes through SSH commands and use Open OCD and GDB to debug M3 nodes remotely. The OML file is used to restore the energy consumption data and the Wire shark is used to analyze the monitored traffic data. Some GPS modules on A8 nodes provide precise end-to-end time synchronization, accurately monitoring and evaluating communication protocols.

Two experiments were carried out on the platform. One is to measure the effect of WIFI traffic under the IEEE802.15.4 network, and to detect the interference of other communication technologies on the same frequency channel by observing the RSSI parameters of the node. The second experiment is using M3 nodes to detect and track human or mobile nodes, mainly using sensors and RF location algorithm. Figure 9, is a system architecture diagram for IoT-LAB. Most of the testing platforms described above are deployed in the laboratory, and there are many large-scale field deployment testing platforms available. For example, FireSenseTB [65] is designed to detect forest fires and used to simulate fire scenarios. SensorScrope [66], which is used to solve the problem that long-term monitoring cannot be maintained in severe environment, is a powerful outdoor environmental monitoring system. There are also some advanced research projects in WSNs field, such as Smart Santander Project Glacs Web project e-SENSE, which are summarized in [67].

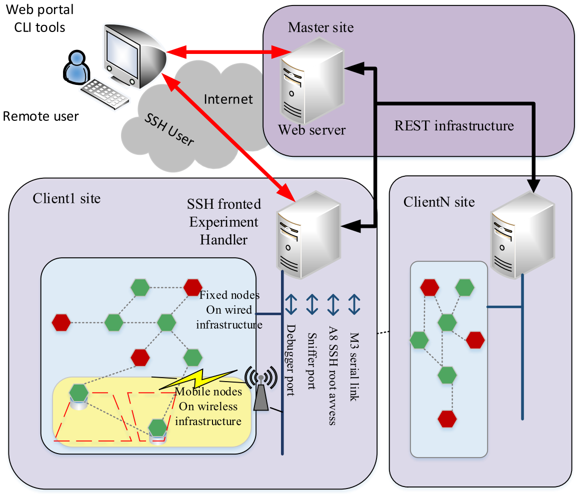

FIGURE 9. IoT-LAB infrastructure.

V. COMPARISON OF HWSNTB

According to the introduction of the third part, we can see that the testing platform has been developing from single application oriented, testing of single protocol algorithm to facilitation, namely supporting a large number of nodes and simulation integration. Different platforms provide different platform construction methods and each one has advantages and disadvantages. The overall comparative analysis is more

TABLE 4. Comparison of characteristics of HWSNTB.

HWSNTB HWSNTB	Custom-build platforms	Multiple OS	Multiple communication technology	Web interface	Simulator integration
Twist	×	×	√	√	×
WSNTB	√	√	√	√	×
EasiTest	√	√	√	√	×
LabVIEW	×	√	√	√	×
Kansei	×	√	√	√	√
SensLAB	√	√	√	√	×
WISEBED	×	√	√	√	√
IoT-LAB	√	√	√	√	×

TABLE 5. Comparison of satisfaction degree of requirements.

HWSNTB	Hetero-geneity	Scala-bility	Porta-bility	Federa-tion	Flexi-bility	Mo-bility	Interac-tivity	Debug-gability	Repeata-bility	Concurr-ency
WSNTB	Yes	Moderate	Better	Moderate	Moderate	No	Good	Better	Moderate	Good
EasiTest	Yes	Good	Better	Good	Good	No	Good	Good	Moderate	Moderate
LabVIEW	Yes	Better	Better	Moderate	Good	Yes	Good	Good	Moderate	Moderate
Twist	Yes	Good	Better	Moderate	Moderate	No	Moderate	Good	Better	Moderate
Kansei	Yes	Better	Good	Better	Good	Yes	Better	Better	Better	Better
SensLAB	Yes	Better	Good	Better	Better	Yes	Better	Better	Better	Better
WISEBED	Yes	Better	Good	Better	Better	Yes	Better	Better	Better	Better
IoT-LAB	Yes	Better	Good	Better	Better	Yes	Better	Better	Better	Better

reliable, and it can also know the focus of each design. Table 4 is from the perspective of the main characteristics of the platform and Table 5 compares the compliance requirements of different platforms. From the comparison results, we can see that the joint platform can meet all kinds of requirements maximally, and the mobile testing platform has more obvious advantages in flexibility.

VI. SUMMARY AND PROSPECT

Information-Centric WSNs are quite different in characteristic from the traditional network. But the performance index that is used to be effective in the traditional network is not necessarily feasible in Information-Centric WSNs, or difficult to quantify into effective, targeted indicators. Therefore, in order to develop new paradigms, Information-Centric WSNs testing is facing many difficulties. However, because of the core technology and related areas of technology gradually mature, a large number of difficult problems can be solved. Through the detailed introduction of the heterogeneous, testing technology and performance evaluation of the testing platform, we can know that the ability of the testing platform to carry the heterogeneous elements is becoming much stronger, and the research direction tends to scale, virtualization and union. This trend guarantees that the network layer in the era of the IoT provides a flexible, simple, connectionless datagram service to the transport layer so as to meet the QoS requirements. What's more, as the technology enters its mature, WSNs will not only be confined to the planet that we live on, but will be linked to outer space. And it will be tested on our gradually improved test bed, which will attain the integration of information. Common testing techniques are few and the accuracy of performance evaluation needs to be improved. In order to make the testing platform more practical and reliable, the following problems need to be solved:

1) With the increasing number of heterogeneous elements in the platform and the integration of various technologies, how to effectively cooperate with each other has become the biggest problem. Because different technologies follow different standards, there may be similarities between mutual interference and incompatibility in the process of using. How to effectively avoid and maximize the use of the advantages of each other needs further study.

2) How to accurately measure the quality of service in a heterogeneous wireless sensor network, is well worth thinking about. Different software/hardware and communication technologies are complex. How to use reasonable and appropriate performance indicators and models to determine testing content and analysis testing results is crucial.

3) Although hybrid simulation testing techniques can provide a variety of testing methods and can be scaled up without deploying more nodes, the effectiveness of the results remains unknown. Therefore, it is necessary to study the corresponding method to determine the accuracy of the testing platform composed of simulation and actual nodes, which is conducive to popularization and application. How can the platform transfer and convert data smoothly in the changing topology of virtual or reality is also a topic worthy of further study.

4) For federated platforms, indeed there are many advantages from the user's point of view. But from the manager's point of view, how to efficiently maintain the large-scale testing platform and how to improve the security and integrity of the platform, these are not short-term problems to be solved, which requiring long-term tracking and much improvement.

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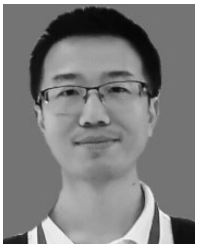

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