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Research and Application of Multimode Communication Technology in Dual Business Scenarios of High-frequency Acquisition and Real-time Monitoring in Distribution Networks

Runhua Yang*, Kaili Dong, Jiao Dong

State Grid Henan Information & Telecommunication company, China

*519271097@qq.com

Abstract

Currently, local communication in distribution network areas mainly uses low-voltage broadband power line communication (HPLC) and wireless private network communication. Low-voltage broadband power line communication technology utilizes existing distribution lines to transmit information, allowing communication to take place without the need for dedicated communication lines, offering advantages such as high reliability, low investment costs, and ease of construction. However, issues such as frequent communication conflicts, poor network scalability, and low transmission efficiency exist in practical applications. This paper investigates the demand for access methods and communication resources in multi-service scenarios for new energy distribution areas, studies the quantified communication resource model, and researches multi-mode fusion communication technologies such as LoRa and power line carrier, as well as hybrid load balancing algorithms. It aims to develop suitable resource allocation strategies and methods for multi-service scenarios, realizing optimal control and management of multi-mode communication resources for new energy distribution areas, effectively suppressing limited/wireless channel resource conflicts under traditional unmanaged modes.

Keywords

Low-voltage Broadband Power Line Communication; Multi-mode Fusion Communication Technology; Hybrid Load Balancing Algorithm.

1. Introduction

With the “dual carbon” goal and the development of the energy internet, the elements of “source-grid-load-storage” in distribution network areas have increased, leading to an explosive growth in the dual demand for high-frequency collection and real-time monitoring. Traditional distribution network communication networks cannot meet the new business communication needs. Therefore, research and application of multi-mode communication technology suitable for the dual business scenarios of high-frequency collection and real-time monitoring in distribution network areas will undoubtedly play an important role in ensuring the communication needs of distribution network areas. Moreover, due to the significant advantages of low-voltage broadband power line communication technology and wireless communication technology in communication quality, security, and reliability, multi-mode communication technology based on carrier and wireless communication technologies is more easily applied and promoted in the power industry and other industrial sectors.

The paper conducts an analysis of information such as the network environment, resource elements, network topology of the distribution network area, and then studies the intelligent access management mechanism based on the entropy weight method and grey relational analysis method. This mechanism

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achieves the optimal control and management of multi-mode communication resources in the new energy distribution network area, effectively suppressing the conflict of limited/wireless channel resources under traditional unmanaged mode. With the mixed load balancing technology, it enhances the utilization of communication channels and fully exploits the channel capacity limit. It breaks through key technologies such as deterministic payload and delay analysis, security isolation and enhancement, time synchronization and scheduling, completing the deterministic quality of end-to-end transmission delay in the coexistence of multiple power business environments, efficiently and reliably transmitting on-site data, ensuring the full-chain security of the new energy distribution network, supporting multi-dimensional data integration applications, facilitating the coordination and interaction of power generation, grid, storage, and consumption in the energy internet, improving the capacity and management capabilities of distributed energy consumption, and supporting the construction of new power systems on the distribution network side.

2. The Study Content, Theoretical Basis, and Implementation Plan

The new distribution network, through its high-speed, bidirectional, and integrated communication system, can continuously self-monitor and self-correct, enabling self-healing functions. Various smart meters, intelligent electronic devices, power electronic controllers, protection systems, control centers, and user information in the new distribution network can only be transmitted through high-speed, bidirectional, and integrated communication systems to achieve networked transmission, thus improving the service level of the distribution network, monitoring various disturbances, compensating, redistributing power flows, and avoiding accident amplification.

Multi-mode communication networks are applied in the new distribution communication system, overlapping and covering intelligent distribution automation, business nodes for smart distribution terminals, distributed energy storage devices, microgrid access, electric information collection, smart meters, and load control management in transformer substations. Through a flexible and reliable wireless self-organizing approach, it forms a robust communication network with stable link quality to adapt to different terrains and different forms of new distribution network architecture, and to achieve reliable and real-time transmission of communication services.

2.1 Theoretical Basis

2.1.1 Research on the Integration of Multi-Mode Networks for Distribution Network Communication

The integration of multi-mode networks is an inevitable trend in the parallel evolution of various wireless networks. In the architecture of multi-mode network integration, the key issue is how to ensure that users can access integrated services with end-to-end guarantees at any time, any place, and for any user. Due to the diverse forms of network resources, varied user service requirements, and unclear commercial operation models in the multi-mode network integration system, the research on multi-mode fusion networks faces many technical challenges and problems. Furthermore, the technical challenges are interdependent, increasing the difficulty of solving these problems. Wireless resource management in the context of the fourth-generation multi-mode fusion network is an important open problem that has been widely researched. Wireless resource management in multi-mode networks is a mechanism and strategy set for effectively controlling the network, completing distributed processing while supporting access control of services, and assisting in improving the utilization of wireless spectrum, thereby maximizing system capacity expansion. Compared with traditional wireless resource management, wireless resources in the multi-mode fusion environment include not only wireless spectrum, but also access permissions for services, transmission power, channel coding, and connection modes. Therefore, the management of wireless resources in multi-mode fusion networks generally expands in two main aspects. First, the composition of wireless resources, which mainly includes the expansion of the value range of resources and the coupling relationships between resources. Second, the variation of resources. In a heterogeneous business access network environment, the changes in various elements of wireless resources in multi-mode

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networks cannot be fully reflected by one-dimensional random variables. Therefore, the composition of wireless resources needs to be represented by two-dimensional or multi-dimensional random variables. The wireless resource management mode in multi-mode networks includes centralized management and distributed management, both of which have their own advantages and disadvantages.

(1) Centralized wireless resource management

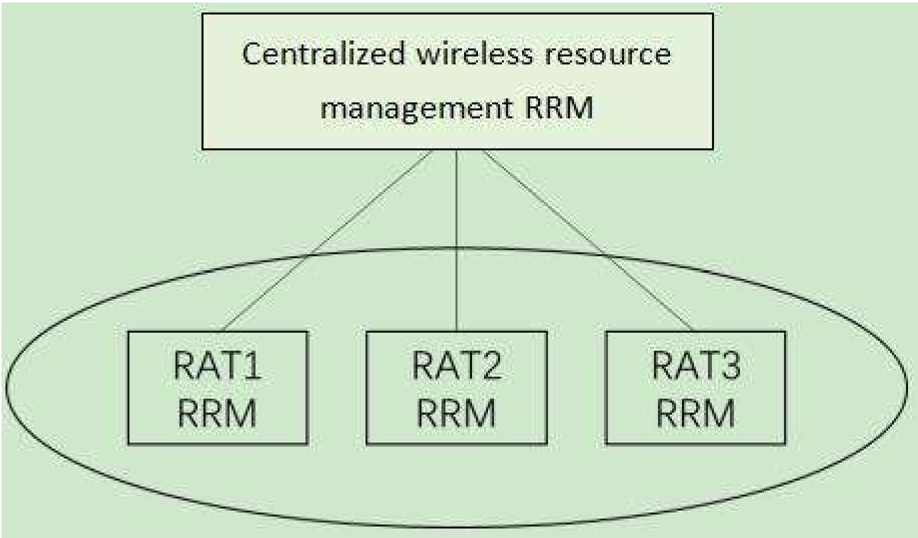

Figure 1. The architecture of centralized wireless resource management

As shown in Figure 1, the architecture of centralized wireless resource management is applicable to tightly coupled converged network architectures. Its centralization is mainly manifested in having a centralized resource management control entity that manages various wireless access networks. It can measure the usage of wireless resources within its jurisdiction and uniformly allocate and manage these resources.

The functional modules of centralized wireless resource management include joint management and independent execution. The joint management entity, serving as the point of wireless resource management execution, operates independently of various wireless access technologies and is mainly responsible for admission control, handover management, resource allocation, and time scheduling. From the perspective of the entire wireless resource management process, the wireless resource management module controls the resources in heterogeneous networks from a macro perspective, while the management and control entities in various wireless access technologies operate in a traditional specific and fine-grained mode of wireless resource management. On the wireless network side, the independent execution entity reports wireless status information and load information to the joint management entity. Then, the joint management entity performs unified wireless resource estimation and allocation, and subsequently sends the distribution plan to the various independent execution entities on the wireless side. The centralized wireless resource management architecture achieves the goal of maximizing system capacity and optimizing global resource utilization through centralized management of resources in its jurisdiction. However, the performance of centralized wireless resource management is poor in terms of flexibility and scalability.

(2) Distributed wireless resource management

In comparison to the centralized wireless resource management mode, the distributed wireless resource management mode does not have a centralized management entity to coordinate various wireless access technologies. As shown in Figure 2, each peer-to-peer wireless access network has unified coordination functionality, which distributes computing and control functions to all distributed nodes to achieve a common goal. Distributed wireless resource management reduces the computational complexity of individual nodes and enhances system redundancy. Specifically, the failure of certain nodes in the network will not cause destructive impacts on the management and computing of other distributed nodes.

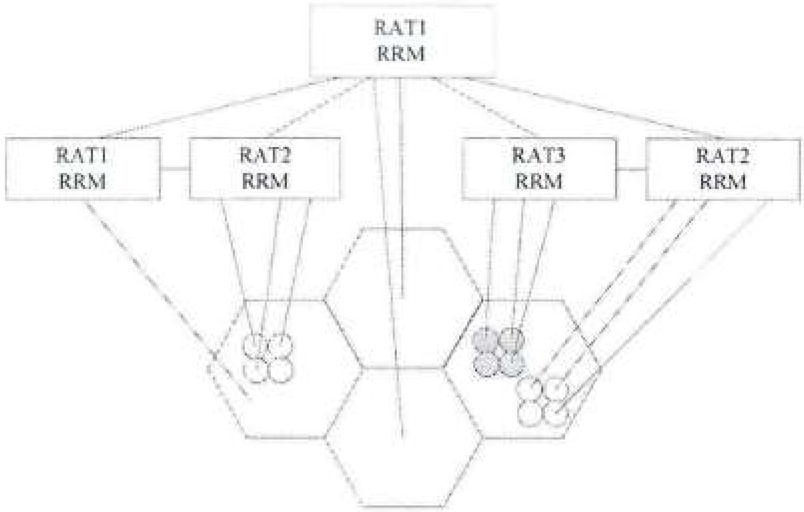

Figure 2. The architecture of the distributed wireless resource management mode

In a distributed management architecture, the wireless resource management entities of various networks need to communicate with each other in addition to completing their own network resource management, to collect information for decision-making strategies such as vertical handover, admission control, and load balancing, and ultimately inform the corresponding wireless resource management entities to execute the decision results. The distributed architecture has the characteristics of good scalability and high flexibility, facilitating management and maintenance, and at the same time, it has a lower dependency on the central decision-making entity. Due to the lack of global information support, even though the overall performance of the system can be improved through information exchange, it is difficult for this architecture to achieve optimal resource utilization. The incomplete and uncertain information may lead to suboptimal global solutions, thereby preventing the overall performance of the system from being better optimized. Additionally, due to the lack of a centralized management entity, the wireless resource management entities can only achieve robustness through a large amount of information exchange by adding additional signaling overhead.

2.1.2 Research on Access Selection and Communication Control Mechanisms in Multi-mode Communication Scenarios

The access selection and admission control of multi-mode converged networks can be achieved by two methods: the terminal actively selects the most suitable network access and the network control center controls and determines whether the terminal is accepted by a certain network based on the overall network performance, thus achieving the optimal state of network resource utilization and terminal service implementation. This mechanism is an indispensable and important part of wireless resource management in multi-mode converged networks and is the primary factor affecting system resource utilization. The differences between different access technologies present great challenges for access selection in heterogeneous wireless network environments. Traditional access selection and admission control algorithms mainly include random access, simple weighted access, multiplicative exponent-weighted access, high-bandwidth priority access, ordinal preference access close to ideal solutions, and grey relational analysis. Most of these algorithms are based on static network parameters and do not consider the dynamic nature and trends of network parameters. Compared to traditional methods, access selection and admission control methods in multi-mode networks are no longer limited to single attribute decision problems, but are multi-attribute decision problems oriented towards the characteristics and requirements of terminals, networks, and users at various levels, and should have good dynamism and adaptability. Their processing is also more complex. Additionally, due to the significant differences in available bandwidth, resource allocation strategies, business type allocation, and negotiation mechanisms among different wireless access technologies, their adopted strategies may also differ significantly. If these wireless access networks are directly integrated without corresponding coordination measures, the multi-mode terminals may experience large horizontal fluctuations when triggering access selection, or even cause connection interruptions. Therefore, to achieve full utilization of wireless network resources while ensuring seamless handover for multi-mode terminals during communication, it is necessary to improve the original access selection and admission control strategies in each wireless access system. In summary, the main problem that access selection and admission control algorithms in multi-mode wireless networks need to solve is how to comprehensively utilize the characteristics of different wireless access technologies to improve the utilization of resources in multi-mode networks while ensuring the quality of service. As the number of candidate networks and decision factors increases, this process will become very complex, requiring comprehensive consideration of various decision parameters and rational trade-offs among user preferences, service requirements, and network conditions to provide reasonable access targets for services.

2.1.3 Research on Multi-mode Communication Load Balancing Technology in Distribution Network Areas

Network load is used to measure the utilization of network resources under certain conditions and environments, usually measured by the number of users that can be accommodated or the amount of available channel resources. The traditional goal of research on network load balancing and control is to improve the utilization of network resources. In traditional single-mode networks, channel borrowing and load transfer are commonly used to achieve load balancing by exchanging channel resources within small cells. Channel borrowing mainly involves overloaded cells borrowing channels from underloaded cells or using shared channels between networks. Load transfer refers to shifting some users from overloaded cells to neighboring cells to achieve an evenly distributed network load. For instance, in a scenario where microcells supplement macrocells, when the macrocell is overloaded, some services can be transferred to the overlapping microcell. With the diversification of service types and service demands in multi-mode networks, the optimization goal of resource allocation and load adjustment is no longer solely focused on improving resource utilization. The development of multi-mode integrated networks has expanded the scope of research on network resource allocation and inter-network load balancing issues to consider subjective factors such as service costs and user satisfaction during the optimization process. Therefore, if traditional load balancing methods based on resource utilization in homogeneous networks are still used in multi-mode integrated networks, the inability to fully consider the multi-modality between networks may lead to an imbalance in traffic or load distribution, resulting in congestion in some networks while other network resources remain idle. In response to the characteristics of multi-mode integrated networks, numerous scholars have conducted research on load balancing algorithms. Literature has proposed a balancing algorithm based on dwell time to select traffic transfer services based on the dwell time of mobile terminals in overloaded networks, which to a certain extent reduces the blocking rate of multi-mode systems and improves resource utilization, but also increases the rate of handovers. Domestic scholars have proposed an improved dynamic threshold joint load control algorithm based on the end-to-end reconfiguration framework, which adopts a targeted load measurement method based on the characteristics of heterogeneous wireless access technologies. This algorithm achieves inter-network load balancing in multi-mode networks through a network-initiated vertical handover process and uses the analytic hierarchy process to address terminal selection issues during the handover process, minimizing the potential impact on users and services, effectively controlling the system's blocking rate and cumulative handover times.

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2.2 Research Content and Implementation Plan

2.2.1 Study the Access Methods and Communication Resource Requirements for Multiple Business Scenarios in the New Energy Substation Area

By modeling the resource elements, optimize the communication requirements for different types of businesses. For control-oriented services, ensure the reliability of terminal communication through capabilities such as anti-interference, fault self-healing, and delay control. For collection-oriented services, meet the access needs of various services through capabilities such as heterogeneous network integration, network agile expansion, and protocol interconnection. For interactive services, improve service friendliness through capabilities such as addressing routing and real-time response. Modeling the substation network environment and network node topology information to improve the communication performance, reliability, and coverage of the physical network, while supporting communication for control, collection, and interaction of multiple business systems.

2.2.2 Study the Applicability of Multi-mode Integrated Communication Technologies Such as LoRa and Power Line Carrier in the Distribution Network Substation

In the new distribution multi-mode communication network environment, wireless multi-mode communication terminals will be widely used in the distribution terminal layer, allowing terminals to freely choose any wireless access network based on their business needs. The terminal will continuously detect the current network environment and collect parameters of each network during communication initiation or process. The network selection control module in the terminal will then select the best network in the current environment based on the collected real-time parameters. The project's access selection algorithm, based on the weighted method and grey relational analysis, can be divided into three main steps: collecting network information, processing information data, and making decisions. In the information processing stage, the algorithm constructs a decision matrix based on received signal strength, remaining available resources, and current business blocking rate. Next, it calculates a grey relational matrix reflecting the performance levels of various access networks through normalization and grey relational calculation. Finally, it calculates the weights of each performance using the weighted method, combines them with the relational matrix, and obtains the performance ranking of heterogeneous networks. In the access decision stage, the terminal is connected to the optimal network according to the ranking results, i.e., the target network.

2.2.3 Research on Hybrid Load Balancing Algorithm based on Multi-mode Communication Technology

Load balancing is an effective way to improve network operation quality and can be used to alleviate or solve the uneven distribution of resources in multi-mode communication networks, thereby improving system capacity and service quality, and increasing the increasingly tight wireless resource utilization. As the business duration and arrival intensity of multi-mode communication wireless systems are dynamically changing, the load levels of various networks in the system also change dynamically. For this reason, the hybrid load balancing algorithm proposed in this project will use the triangular fusion operator to measure the real-time load level of the network. For overloaded networks, a suitable amount of business will be swithed to lightly loaded networks for service; and by using access control strategies based on resource reservation and preemption priority, different types of new power distribution communication services will be served according to service priority. This method can balance the load between networks during busy and idle times, while ensuring that high-priority services are reliable and efficiently delivered, it also appropriately reduces the blocking rate of low-priority services. Therefore, this method has good dynamic adaptability to the real-time changes in network load levels.

2.2.4 Development of Multi-mode Communication Module Integrated with Lora and Power Line Carrier Technology

Relying on the intelligent integrated terminal in the distribution area, a multi-mode communication module integrating LoRa and power line carrier technologies will be developed. This will virtualize the multi-mode communication resources in the distribution area and deploy micro-applications in

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the integrated terminal to achieve intelligent allocation and balancing of communication resources. While meeting the requirements of high frequency, high precision, and real-time response, it will also be able to flexibly tailor communication resources based on business and environmental conditions, enabling intelligent management and catering to the diverse needs of large-scale, efficient, intelligent, reliable, low-latency, deterministic, and endogenous secure service in the "dual-carbon" scenario of the active distribution network. Additionally, the network will possess capabilities such as open scalability, incremental deployment, and heterogeneous integration, supporting on-demand reconstruction of the network and rapid access of new services. This will provide solid communication support for the power communication network in the emerging power system.

3. Conclusion

In conclusion, we have developed optimal communication resource allocation methods for high-frequency data acquisition and real-time monitoring in active distribution networks. These methods aim to enhance the capacity and service quality of multi-mode communication systems, and improve the utilization of carrier and wireless bandwidth resources. Additionally, we have designed a multi-mode communication module integrating LoRa and power line carrier technologies, equipped with intelligent access mode selection and resource allocation strategy models. This module meets various differentiated requirements for efficient, intelligent, reliable, low-latency, deterministic, and endogenous secure communication in the "dual-carbon" scenario of the active distribution network. It effectively ensures the efficient and reliable transmission of on-site data, safeguards the end-to-end security of new energy distribution communication networks, supports multidimensional data fusion applications, facilitates the interaction and coordination of generation, grid, load, and energy storage in the energy internet, and enhances the capability and management of distributed energy integration. This will contribute to the construction of a new type of power system in the distribution network.

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