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TOPICAL REVIEW

An Comprehensive Overview of Electric Power Wireless Private Network: System Design, Key Technologies, and Future Directions

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ABSTRACT Currently, commercial cellular public networks such as 4G/5G have been widely deployed in China. In addition to serving general public customers, they are extensively used in the electric power industry for electricity information acquisition and distribution automation telemetry, as well as other non-control-related businesses. Simultaneously, power grid companies are actively studying and deploying electric power wireless private networks for bearing high-security control-related businesses such as distribution grid dispatching and distributed energy control. Electric power wireless private networks utilize dedicated spectrum resources, which operate on narrow individual carrier channels with numerous carriers in a discrete manner. These spectral characteristics indicate that electric power wireless private networks require unique system designs that are different from those of commercial cellular networks. Although some proposals have been proposed in relevant research, a unified and mature technical specification for electric power wireless private networks has not yet been established. This paper introduces the development history of electric power wireless private networks and power grid business requirements, with a specific emphasis on system design and key technologies, including frame structure and numerology, massive discrete carrier aggregation, spectrum sensing, security and isolation. We presented a comprehensive analysis and suggestions for these key technologies. Finally, we discuss future research on technological evolution. This study offers indications for an electric power wireless private network ecosystem.

INDEX TERMS EP-WPN, system design, massive discrete carrier aggregation, future.

I. INTRODUCTION

The power grid is a crucial infrastructure for a country's economic and social development, and electric power communication is an important technical support for achieving a smart-grid strategy. In various links such as power generation, transmission, transformation, distribution, and consumption, power communication provides effective and reliable communication channels for various power businesses, including power equipment measurement and monitoring, power generation and load control, power consumption information acquirement, and interaction between source, network, load, and storage. Electric power communication is usually implemented using an optical fiber network in transmission lines and substations above 35kV/10kV, which is called an electric power backbone communication network. On the other hand, wireless communication is mainly used for the distribution and consumption sides of 10kV and below, which is called the electric power access communication network. The electric power access communication network is used to provide wireless communication points conveniently, quickly, and at low cost. It satisfies the access requirements of a large number of power terminals for distribution automation, accurate load control, and power consumption information acquisition. The technical type includes cellular wireless public network and electric power wireless private network (EP-WPN). The cellular wireless public network mainly carries services such as information collection,

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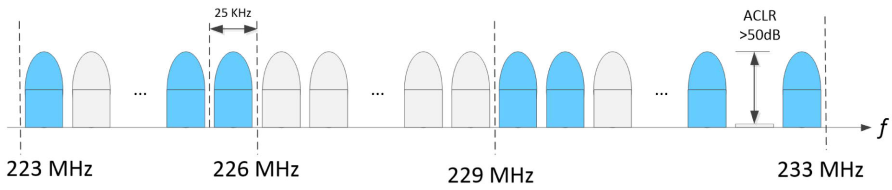

FIGURE 1. The frequency for EP-WPN.

TABLE 1. Summary of related surveys on EP-WPN.

Ref.	Research	Year	vision/ requirements	Architecture/ Technologies	Trial/ Use Cases	Challenges/ Future	Contributions
[17]	X. Chen *et al.*	2020	L	M	H	L	Performance Optimization based on Network Planning
[10]	W. Zheng *et al.*	2020	L	M	L	H	NOMA for EP-WPN
[14]	C. Zhang *et al.*	2020	L	M	H	L	Performance Optimization based on Joint Detection
[11]	M. Yang	2020	L	H	L	M	Spectrum Sensing
[12]	J. Tong *et al.*	2020	L	H	L	M	Interference Avoidance Strategy in 230 MHz
[6]	L. Zhong *et al.*	2020	M	H	L	L	Hierarchical networking architecture
[8]	X. Zhao *et al.*	2019	L	M	L	H	Adaptive Carrier Aggregation
[7]	H. Zhu *et al.*	2019	L	H	L	L	security
[15]	Y. Wang *et al.*	2019	L	H	L	L	Antenna Design
[16]	J. Yao *et al.*	2018	M	H	L	L	Architecture Design
[9]	C. Zhou *et al.*	2018	L	H	L	L	Intermediate Frequency Design
[13]	J. Wang *et al.*	2017	L	H	L	M	Spectrum Detection
	Our study	2023	H	H	H	H	Timeline, Vision, Architecture, Breakout Technologies, Future Research

whereas the EP-WPN mainly bears power control-related services.

In China, 223MHz-235MHz is the frequency band designated by the State Radio Regulatory of China (SRRC) for telemetry, remote control, and data transmission. The total bandwidth of the 230MHz frequency band is 12MHz, divided into 480 frequency subbands [1], and each frequency subband corresponds to a bandwidth of 25kHz, also known as a carrier or a channel. The SRRC authorizes the power industry to use a 7MHz bandwidth from 223MHz-226MHz and 229MHz-233MHz, corresponding to 278 discrete distributed carriers [2], as shown in Fig. 1. Within the 7MHz bandwidth, 43 scattered carriers are already occupied by other industries such as meteorology, water conservancy, and geology, which are not available to the power industry. Therefore, the power industry can use a total of 235 discrete distributed carriers. The SRRC specifies that traditional digital radios generally use a single 25kHz channel. To avoid adjacent channel interference, multiple 25kHz carriers cannot be used consecutively. Each channel should reserve sidebands to satisfy the adjacent channel leakage ratio(ACLR) requirement, as illustrated in Fig. 1.

EP-WPN has a long history, dating back to 1991 when the SRRC authorized the power industry to use 40 carriers in the 230MHz frequency band [3], including 15 pairs of FDD carriers and 10 pairs of TDD carriers. It used frequency-shift keying technology, with a rate of only 9.6kbps. It is mainly used for point-to-point transmission of power load telemetry services and does not have networking capability. With the commercial deployment of 4G LTE public network in the 2010s, some researchers creatively applied OFDM and carrier aggregation(CA) technology to 40 discrete carriers [4], [5], significantly increasing the transmission rate to over 1Mbps. With the development of the smart grid, the power industry obtained authorization for 7MHz bandwidth in 2018 to meet the growing demand for new power services such as active power distribution and distributed generation sources, which require a higher traffic volume. Furthermore, a series of research results have emerged in various key technical aspects of the 7MHz EP-WPN system, such as network architecture [6], data security [7], carrier aggregation [8], [9], multiple access [10], spectrum sensing and interference avoidance [11], [12], [13], signal detection [14], [15], high-level protocol stack [16], and network planning [17].

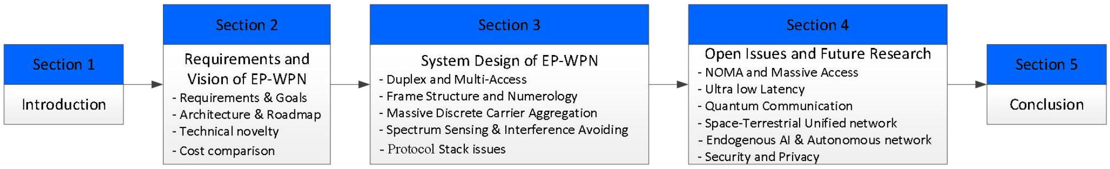

FIGURE 2. Structure of the paper.

TABLE 2. Summary of related surveys on EP-WPN.

Acronym	Definition	Acronym	Definition
EP-WPN	Electric Power Wireless Private Network	QoS	Quality of Service
AI	Artificial Intelligence	SRRC	State Radio Regulation Committee
NOMA	Non-Orthogonal Multiple Access	IF	Intermediate Frequency
QC	Quantum Computering	V2G	Vehicle to Grid
FDMA	Frequency Division Multiple Access	TDMA	Time Division Multiple Access
OFDMA	Orthogonal Frequency Division Multiple Access	IoT	Internet of Things
Half-FDD	Half Frequency Division Duplex	TDD	Time-division Duplex
FDD	Frequency Division Duplex	CA	Carrier Aggregation
SDN	Software-Defined Networking	NFV	Network Functions Virtualization

Table 1 summarizes the relevant research results from recent years.

Power grid enterprises are the main entities responsible for constructing, operating, and using electric power wireless private networks. From 2018 to 2019, power grid enterprises conducted trial network testing and verification of the critical technologies and networking capabilities of EP-WPN, and carried out end-to-end QoS adaptability verification for various power services. This initially proves its technical feasibility. However, in May 2019, 5G began to be commercially deployed on a large scale, and operators vigorously promoted 5G applications for ToB targeting vertical industries while providing ToC services to the public. In this context, some hold the opinion that 5G commercial networks can meet all business scenarios of the power industry by using the slicing virtual private network method owing to its characteristics of eMBB, uRLLC, and mMTC. Therefore, it is no longer necessary to develop and construct an EP-WPN. The power grid enterprises decided to suspend and freeze the EP-WPN technology standardization and network deployment process in August 2019, and turned to test the feasibility of 5G virtual private networks for power businesses.

After three years of large-scale testing and verification of the 5G virtual private network for the power industry from 2020 to 2022, and comparing it with the EP-WPN, some issues were found regarding the transmission latency jitter and data security protection of the 5G virtual private network. The high security, low latency, and high deterministic transmission requirements of power grid control businesses cannot be fully satisfied by 5G technology. Moreover, the cost of exclusive isolated network resources such as the spectrum, UPF, and network management interface provided by public operators to electric power users is considerably high. With the rapidly increasing number of industrial users, the cost of 5G virtual private network has increased significantly, failing to demonstrate the cost advantage of avoiding network construction.

Because SRCC currently does not authorize the power industry to have a dedicated spectrum for private 5G, power grid enterprises believe that EP-WPN is more suitable to bear power control-related businesses. EP-WPN technology optimization and evolution were re-launched in 2023.

This paper discusses the key technology, system design and future challenges of the EP-WPN in detail. Section II presents the characteristics of power businesses, design goals, architecture and roadmap, technical novelty and cost comparison of the EP-WPN. Section III presents the system design and basic key technologies of the EP-WPN. Section IV provides a brief overview of open issues and their future evolution. Finally, Section V presents our conclusions.

The structure of this work is presented in Fig. 2. For the convenience of following the article, the acronyms are compiled in Table 2.

II. VISION AND REQUIREMENTS OF EP-WAN

A. CHARACTERISTICS OF ELECTRIC POWER BUSINESSES AND REQUIREMENTS FOR EP-WPN

The various electric power businesses are divided into three major security sections according to different security level requirements: production control section, information management section, and Internet section. The main production control services are listed in Table 3.

Information monitoring and management businesses mainly include online monitoring of power transmission lines [18], environmental monitoring of cable tunnels, monitoring of distribution rooms, comprehensive monitoring of substations, converter stations, charging stations or battery swap stations [19], power consumption information acquisition [20], intelligent mobile inspection by unmanned aerial vehicles (UAVs) or robots [21], [22], and mobile offices. The Internet business mainly involves businesses such as virtual power plants [23] and integrated energy [24]. The transmission characteristics of the two types of businesses are mainly small packet data at tens of kbps and audio/video data at Mbps levels.

Production control businesses have extremely high requirements for the security and reliability of communication systems, with strict requirements for system latency and routing [25]. However, communication failure may affect the execution of power grid control, leading to grid operation faults [26]. Conversely, information monitoring businesses have lower security, reliability, and latency requirements [27]. Communication failure may have an impact on grid operation management, but will not cause grid failure or paralysis.

It can be seen that the characteristics of various types of electric power business are different, including high-speed data services and small packet low-latency and high-reliability precise-control services, which have different requirements for electric communication bandwidth, latency, and reliability. Therefore, the requirements for electric power communication are derived: how to design an EP-WPN system on 280 discrete 25KHz radio carriers dedicated to the electric power industry, which can integrate wideband and narrowband, allocate resources flexibly, and ensure security and reliability ?

B. GOALS OF EP-WPN

Based on the characteristics of electric power businesses [28], it is difficult to bear large amounts of high-speed audio and video services owing to the 7 MHz bandwidth limitation. Therefore, EP-WPN and electric power 5G virtual private network (VPN) based on commercial operator networks should focus on different aspects and complement each other. Considering the importance and security of industry data, EP-WPN mainly bears electric control businesses and sensor monitoring small packet services, whereas the electric power 5G virtual private network mainly bears large-bandwidth audio and video services and other information management businesses that do not involve electric dispatch control.

The power grid is deployed hierarchically, and different businesses are regulated and controlled according to their security levels. EP-WPN technologies must take into account the characteristics of the grid businesses and their applications. The main objectives of the EP-WPN are as follows.

1) HIGH RELIABILITY

To achieve coordinated control of the entire electric power system, the reliability of the grid control business should be greater than 99.999%, whereas the reliability of the information monitoring and acquisition business should reach 99.99%. The EP-WPN should meet these requirements [14].

2) LOW LATENCY

To better control and protect the distribution grid, there are corresponding requirements for load control based on user response and distribution micro synchronous measurement in terms of latency. The former requires a latency of no more than 20 ms, whereas the latter requires a latency of less than 10 ms. At the same time, these low latency control instructions require the EP-WPN to have end-to-end deterministic transmission capabilities.

3) INTELLIGENCE

The EP-WPN should support the characteristics of digital twin and network endogenous intelligence, including the ability of adaptively constructed network topology [29], adaptively coordinated network interference, transparently monitoring network quality, and adaptive transmission visualization.

4) ELASTICITY

For various electric power business scenarios with different scales of business volume, user number, and service quality, the EP-WPN should be able to adapt elastically to different businesses. Network cloud computing capabilities, edge computing capabilities [30], and terrestrial and space-based intelligent network topologies can be elastically and flexibly software-defined, building a resilient private network with strong infrastructure, comprehensive coverage, advanced technology, and sufficient resources.

5) SECURITY

The EP-WPN is mapped to three major security partitions: the internet section, the information management section, and the production control section, which are separated from each other by physical isolation and logical isolation methods. With the access of massive new energy terminals, to ensure access control, it is necessary to adopt appropriate lightweight security authentication and encryption technology to achieve effective security isolation [31], meet high-throughput requirements, and build a security guarantee system with equipment trustworthiness, status awareness, reliable methods, and controllable risks.

C. ARCHITECTURE AND ROADMAP

For the above objectives, to better ensure network latency, security, and hierarchical control, the network architecture

TABLE 3. Production control services for electric power.

Service Type	Latency	Rate	Reliability	User dense per km^2	Concurrency
Precise load control	50ms	22.4kbps	99.999%	2	50%
Distribution Automation	2s	19.2kbps	99.99%	13	60%
Distribution Differential Protection	10ms	4Mbps	99.999%	4	50%
Remote control of distributed generation and energy storage	2s	45kbps	99.99%	20	50%
load control	3s	2.5kbps	99.99%	18	20%
Power information acquisition with power-on / off function	3s	1.05kbps	99.99%	763	20%
Control of the charging station supporting V2G	2s	20kbps	99.99%	15	40%

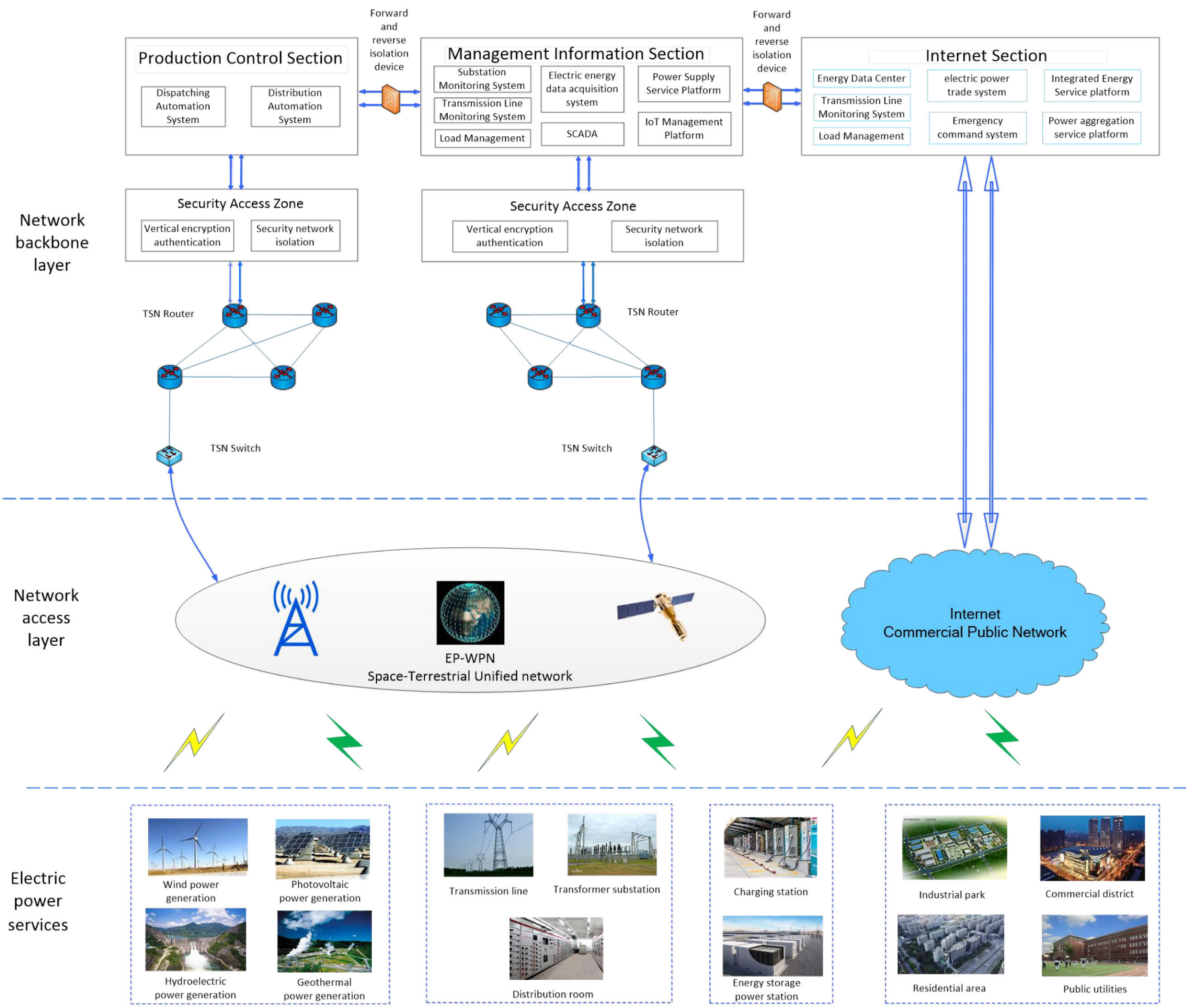

FIGURE 3. The EP-WPN architecture.

of EP-WPN is suitable for adopting a centralized network topology instead of a distributed one [6], which can better match the characteristics of electric power businesses' centralized and hierarchical management, and better integrate

TABLE 4. The key feature comparison of EP-WPN releases.

Feature	EP-WPN Release 1	EP-WPN Release 2
Release Time	2024	2030
Latency	40ms	10ms
Frequency Band	230MHz	230MHz
Connection Density	3000 devices/Km2	10000 devices/Km2
Network Type	SDN, NFV, Slicing	SDN, NFV, AI-based Slicing, Intelligent Cloud, Deep Learning
Technique Computing	Edge Computing, Cloud Computing	Edge Computing, Cloud Computing, Quantum Computing
Technology	OFDM, Spectrum Sensing, Discrete Carrier Aggregation	NOMA, Quantum Communications, Endogenous AI, Ultra low delay, Smart Carrier Aggregation, Space-Terrestrial Unified Access,

TABLE 5. The comparison of EP-WPN with digital transmission radio and5G virtual private network.

Feature	EP-WPN	230 Radio Terminal	5G Virtual Private Network
Deploy Time	2024	1990s	2020
Frequency Band	230 MHz	230 MHz	2.6GHz, 3.5GHz
Bandwidth	7 MHz	25KHz	100 MHz
Connection Density	3000 devices/Km2	Point to point	10000 devices/Km2
Networking	Centralized	None	Centralized
Technique Computing	Edge Computing, Cloud Computing Quantum Computing	None	Edge Computing, Cloud Computing
Technology	OFDM, Spectrum Sensing, Massive Discrete Carrier Aggregation, End to End Isolation	GMSK	PRB Reservation, Slicing, Edge UPF Reservation,
Cost	Medium	Low	High

the private network's function elements with electric power business main stations and edge computing. The network architecture of the EP-WPN is shown in Fig. 3.

Aiming at key issues such as discrete aggregation, frame structure and numerology, and interference coordination of 230MHz frequency band dedicated to the electric power industry, we conducted a targeted analysis and presented a recommended solution. Through technological innovations in various aspects of the network access layer and backbone layer, such as digital intermediate frequency, baseband, protocol stack, security and control, an EP-WPN with high reliability, low latency, intelligence, elasticity, and high security is constructed, which can satisfy the demands of the above-mentioned electric power businesses.

Currently, the electric power and the communication industries are collaborating to optimize and improve the EP-WPN technical solution based on initial proposals in 2019. According to the above objectives, the roadmap is planned into two stages: first, EP-WPN Release 1 is formed in 2025 with basic functions; second, EP-WPN Release 2 is specified in 2030 with more advanced technology features. The main features of the two versions of the EP-WPN are summarized in Table 4.

D. TECHINICAL NOVELTY AND COST COMPARISON

At present, in the 230MHz frequency band dedicated to the electric power industry, the most widely used technical approach is the digital transmission radio, which only supports one carrier, corresponding to a bandwidth of 25KHz, only supports point-to-point transmission, and can not be networked. It is mainly used in the collection of telemetry information for power distribution and has problems such as low efficiency and low reliability.

Aiming at the characteristics of 230MHz electric power dedicated spectrum, where individual carriers are narrowband, large in number and discrete in distribution, EP-WPN adopts advanced large-scale discrete carrier aggregation, low-latency frame structure and numerology, OFDM, spectrum sensing, end-to-end security isolation, and other technical designs, solving the problems of wide-narrowband integration, flexible allocation of resources, security and reliability. EP-WPN draws on some of the advanced design concepts of 5G technology and has reached the highest technical level in private industry networks.

Compared to the 230MHz digital transmission radio, EP-WPN boasts more advanced technology. By adopting a centralized control structure, the EP-WPN enables cellular networking and can simultaneously carry multiple electric power business applications. It supports spectrum sensing and interference coordination functions, being able to avoid interference from other 230MHz radios and ensure more reliable data transmission. Furthermore, the EP-WPN can accommodate a larger user capacity, enabling wide-area electric power regulation and control. Finally, it implements end-to-end secure isolation, ensuring the security and trustworthiness of the electric power control services.

Compared to the commercial operators' 5G virtual private networks, the EP-WPN employs a physical private network architecture, ensuring exclusive use for the electric power industry. This approach only requires investment in construction, operation and maintenance costs, eliminating expensive network leasing and terminal service fees. Additionally, the EP-WPN offers end-to-end transparency and controllability, warranting the security of sensitive data within the electric power industry.

The 5G virtual private network service provided by commercial operators requires electric power users to lease dedicated UPF, dedicated PRB, dedicated transport-bearer network, dedicated core network elements, and so on, in addition to the service fees for each communication terminal. According to the calculations, with a total cost of 10 years, the cost of EP-WPN is only approximately one-third that of the operator's virtual private network, which is more economical.

A comparison of EP-WPN with digital transmission radio and 5G virtual private network is presented in Table 5.

III. SYSTEM DESIGN AND KEY TECHNOLOGIES OF EP-WPN

EP-WPN has now developed a preliminary technical scheme, but has not yet finalized an agreed-upon Release 1 solution. This section discusses some of the key technologies involved in the EP-WPN Release 1 system design and provides our analysis and suggestions.

A. DUPLEX AND MULTI-ACCESS

In the existing 230MHz electric power communication, digital radios are mainly used. In the 1990s, analog radios were used with communication rates below 1.2kbps. In the 2000s, digital signal processing, digital modulation and demodulation technologies were adopted, which increased the transmission rate to more than 19.2kbit/s. Digital radios use FDD or Half-FDD modes and support only point-to-point communication. Different terminal users are distinguished by occupying different carrier pairs(i.e., FDMA), thus adopting a polling method to complete the communication between multiple terminal radios and one base station radio. When there are too many terminals connected to the same service master station, the polling time is too long to meet the massive access requirements of the smart grid.

Regarding the duplex mode, considering that the acquisition and monitoring services of the electric power business account for the majority, the data transmission direction is uplink, sent from the terminal to the electric master station, and the data rates of control commands sent from the downlink electric power master station are low, so all manufacturers in the industry have agreed to adopt the TDD mode in order to flexibly adapt to the needs of various businesses.

EP-WPN,as an upgrade and replacement technology for digital radio, supports the simultaneous access of a large number of users. It can adopt orthogonal frequency division multiplexing technology to finely divide each 25KHz carrier into more subcarriers, supporting more user access and higher resource utilization by combining 278 discrete carrier resources and different time intervals(i.e.,FDMA and TDMA). Thus, all manufacturers in the industry unanimously agreed to adopt OFDMA, FDMA, and TDMA as multiple access modes of EP-WPN.

B. FRAME STRUCTURE AND NUMEROLOGY

Frame structure and numerology are fundamental parameters for physical layer design in wireless communication systems, and are also key technical points in the design of communication systems. In the current technical discussion of the EP-WPN, two proposals have been presented. Both proposals adopt a TDD frame structure, with one radio frame divided into five subframes, including one special subframe for uplink-downlink switching and synchronization signals transmission. However, the frame length, subcarrier spacing, and time-frequency resource parameter values are different between the two proposals.

In proposal 1, the baseband sampling rate is 128ksps, i.e., Ts = 1/128000s. The length of one radio frame is 25ms, divided into five subframes, each with a duration of 640Ts. Subframe 0 is a downlink subframe, subframes 2, 3, and 4 are uplink subframes, and subframe 1 is a special subframe consisting of three fields: DwPTS, GP, and UpPTS, as illustrated in Fig.4. The length of one OFDM/SC-FDMA symbol is 64Ts, and one subframe includes nine OFDM symbols. The length of the first symbol's CP is 8Ts, and the CP lengths of the other eight symbols are 7Ts.

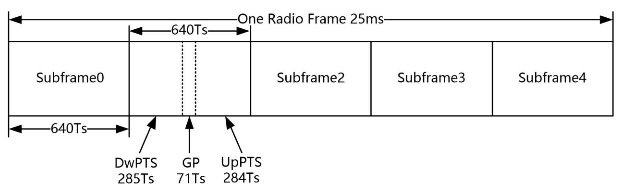

FIGURE 4. Frame structure of proposal 1.

In proposal 2, the baseband sampling rate is 60ksps, i.e., Ts = 1/60000s. One raidio frame has a length of 10 ms and is divided into five time slots, each with a duration of 2ms, i.e.,120Ts. Subframes 0 and 1 are downlink subframes, subframes 3 and 4 are uplink subframes, and subframe 2 is a special subframe consisting of three fields: DwPTS, GP, and UpPTS. The length of one OFDM/SC-FDMA symbol is 16Ts, and each time slot includes six OFDM symbols. The length of the CP is 4Ts.

TABLE 6. Numerology Comparison of Proposal 1 and Proposal 2.

Numerology	Proposal 1	Proposal 2
Radio Frame length	25ms	10ms
Baseband Sampling Rate	128Ksps	60Ksps
Subframe number within a Radio Frame	5	5
Subframe length	5ms	2ms
Subcarrier Space	2KHz	3.75KHz
Sampling points within a subframe	640Ts	120Ts
FFT points	64	16
Subcarriers numbers within a 25KHz channel	11	6
OFDM/SC-FDMA Symbol Number within a subframe	9	6
Cyclic prefix length	8Ts for 1st symbol, 7Ts for The other symbols	4Ts
CP overhead ratio	10%	20%
special subframe position	Subframe 1	Subframe 2
DwPTS:GP:UpPTS	285Ts:71Ts:284Ts	20Ts:40Ts:60Ts

TABLE 7. Resource Utilization Comparison of Proposal 1 and Proposal 2.

Numerology	Proposal 1	Proposal 2
Data Subframe Ratio	97.78%	93.33%
OFDM Symbol Utilization Ratio	90%	80%
Frequency efficient bandwidth Ratio	88%	90%
Total Resource Utilization Ratio	77.44%	67.2%

TABLE 8. Theoretical Peak Rate of Proposal 1 and Proposal 2.

Peak Throughput(kbps)		1 carrier	4 carriers	8 carriers	16 carriers	40 carriers	80 carriers	140 carriers	200 carriers
Proposal 1	Uplink	50.9	208.8	417.8	840.9	2107.8	4215.6	7377.3	10539
	Downlink	21.9	76.5	177.8	385.9	1009.7	2019.4	3533.9	5048.5
Proposal 2	Uplink	28	114	229	458	1145	2290	4008	5725
	Downlink	17	68	139	278	695	1390	2433	3475

A comparison of the numerologies of the two proposals is shown in Table 6.

Currently, these two proposals are deadlocked, and each side believes that their own scheme is superior. In this regard, the following aspects were analyzed and evaluated.

1) RESOURCE UTILIZATION

For a wireless communication system with time-frequency two-dimensional resources, the system performance is limited by its resource utilization efficiency under the same bandwidth constraint. The time domain resource utilization is mainly related to the ratio of CP overhead, and the frequency domain resource utilization is mainly related to the bandwidth ratio of the effective subcarriers. In addition, the effective data transmission frame length is related to the GP ratio. Therefore, the calculation method of resource utilization is to multiply the ratio of data frames without GP by the ratio of effective symbols without CP, and multiply by the frequency domain effective bandwidth ratio. A comparison between the two proposals is presented in Table 7. It can be seen that proposal 2 has a lower overall resource utilization owing to the relatively large CP overhead and higher GP proportion of short frames.

2) THROUGHPUT

Because proposal 2 has a lower overall resource utilization than proposal 1, it will affect its system throughput. For different service terminals, different capability levels can be designed to support different numbers of transmission subbands, thereby achieving different transmission rates to adapt to different service requirements. According to the current design, proposal 1 only supports single antenna transmission, whereas proposal 2 supports dual antenna port transmission. After deducting the common overhead such as the pilot and control channels, the theoretical peak rate is calculated, as shown in Table 8.

3) COVERAGE RADIUS

The coverage radius is mainly determined by the GP length when there is no radio power limit. Based on the GP values

TABLE 9. Transmission Latency Analysis for Proposal 1 and Proposal 2.

Proposal	Scheduling Case	Fault Condition	Latency range(ms)	Average Latency(ms)
Proposal 1	Single Carrier	PDSCH 1st Transmission Successfully	32.7-57.2	44.7
		PDSCH 2nd Transmission Successfully	132.7-157.2	144.7
	Multi Carriers	PDSCH 1st Transmission Successfully	7.2-32.2	19.7
		PDSCH 2nd Transmission Successfully	82.2-107.2	94.7
Proposal 2	Grant, Truncated frames	PDSCH 1st Transmission Successfully	13-23	18
		PDSCH 2nd Transmission Successfully	43-53	48
	Grant, Normal frames	PDSCH 1st Transmission Successfully	14.3-24.3	19.3
		PDSCH 2nd Transmission Successfully	54.3-64.3	59.3
	Grant free, Truncated frames	PDSCH 1st Transmission Successfully	3-13	8
		PDSCH 2nd Transmission Successfully	23-33	28
	Grant free, Normal frames	PDSCH 1st Transmission Successfully	4.3-14.3	9.3
		PDSCH 2nd Transmission Successfully	34.3-44.3	39.3

in Table 6, proposal 1 supports a maximum cell radius of 83 km, whereas proposal 2 supports a maximum cell radius of 100 km. Both meet the wide coverage requirements of low-frequency bands in rural power distribution networks. Because proposal 2 supports a dual antenna port transceiver and adopts SFBC to improve reliability, its performance is superior to that of proposal 1 at the edges of cells with the same radius.

4) MOBILITY

Power unmanned aerial vehicles and robotic intelligent inspection typically move at speed of 4-8 m/s, or less than 30 km/h, and emergency communications typically operate at speed of no more than 60 km/h. The Doppler frequency offset of high-speed movement will have a negative impact on the performance of OFDM demodulation. The subcarrier spacing of proposal 2 is 3.75kHz, and its demodulation performance is better than that of proposal 1 in the simulation, as shown in Fig. 5.

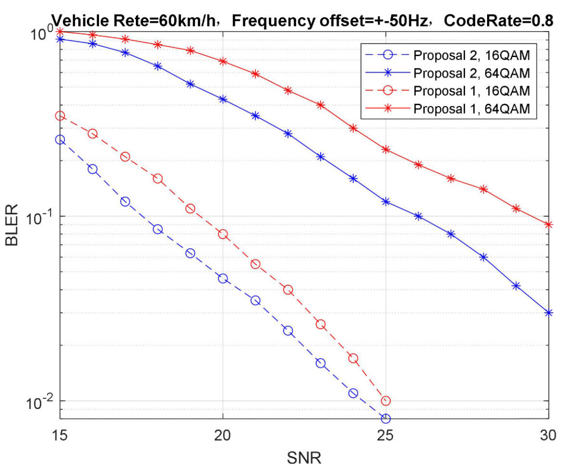

FIGURE 5. Demodulation performance comparison of proposal 1 and proposal 2.

5) TRANSMISSION LATENCY

The radio frame of proposal 2 is 10ms, and its HARQ retransmission interval is shorter, which is beneficial for low-latency services. In order to further reduce the delay, a mechanism of grant-free scheduling and truncated frame transmission is adopted. Proposal 1 only supports scheduled transmission, and the retransmission delay is larger owing to its radio frame length of 25ms. According to the resource allocation and scheduling transmission mechanisms of the two current proposals, the transmission latencies of the two are analyzed as shown in Table 9. It can be seen that the requirement of 50ms latency limitation for the precise load control service can only be satisfied when the PDSCH first transmission is correct in proposal 1. Owing to the randomness and time variability of the fading channel, it is difficult to correctly transmit 100% in a single transmission. In the scheduling transmission of proposal 2, the two transmissions of the normal frame will exceed 50ms. If truncated frames are used, the transmission time of the two PDSCHs can be reduced to within 50ms. Furthermore, when adopting grant-free scheduling transmission, even normal frames can meet the latency requirement. However, for the ultra-low latency requirement of distribution differential protection, it is difficult for both proposals to meet the 20ms delay requirement while guaranteeing the reliability of data transmission.

From the comparison above, we can conclude that the two proposals have their own advantages and disadvantages. Proposal 1 has a higher peak throughput, whereas Proposal 2 has better edge user performance and great advantages in terms of latency owing to its short-frame structure. The performances of proposal 1 and proposal 2 in each of the above aspects were analyzed and discussed in detail in the literature [4] to [17].

In our opinion, considering that 3.75KHz is a multiple of 15KHz, which can better reuse the existing mature 4G and 5G industry chain, it is recommended to consider proposal 2 as the baseline and optimize and modify the frame structure and parameters, called candidate proposal, and its design highlights are as follows.

1) Radio frame structure. We recommended to modify the radio frame length to 5ms, which corresponds to 1ms for each subframe and contains three OFDM symbols. The corresponding time lengths for the DwPTS, GP, and UpPTS are all 1/3ms.The GP time is smaller, which affects the maximum cell coverage radius from 100Km to 50Km.Considering the limitations of the actual base station and terminal transmitting radio power, the coverage radius distance will not exceed 30Km because of the uplink coverage constraints even in rural areas; therefore, this modification will not affect the actual network coverage deployment. Multiple discrete carriers are divided into broadcast access carriers pool and traffic carriers pool. On the traffic carriers, the DwPTS and UpPTS are not used independently but are jointly allocated with the adjacent downlink or uplink subframe. The initial user access and synchronization process is carried out on the broadcast carriers. In order to enhance the uplink random access energy and speed up the access process, the UpPTS and the subsequent uplink subframe jointly carry the uplink synchronization sequence on the broadcast carriers.

2) Subcarrier space. From the perspective of system resource utilization and electric power business application requirements, multiple subcarrier space configurations should be adopted to adapt flexibly to various services. It is recommended to support two subcarrier space configurations of 3.75KHz and 7.5KHz. For different electric power services, multiple discrete traffic carriers are divided into different traffic carrier pools and different subcarrier space configurations are applied. For a long period of small packet acquisition service, using a small subcarrier space configuration, the radio channel can be allocated in accordance with a single subcarrier multi frames, which can improve the efficiency of the control channel and the long-period frequency division of resources. For control services with low latency requirements, a larger subcarrier space and a short OFDM symbol period are adopted to reduce the transmission delay as much as possible.

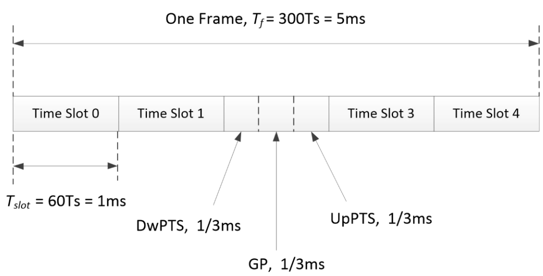

FIGURE 6. Candidate proposal of our optimization study.

The candidate proposal is shown in Fig. 6, and it can be seen that by adopting the frame structure and numerology of our recommendation, the transmission delay is reduced by half compared to proposal 2. At this time, only normal frame transmission needs to be specified, and there is no need to introduce the concept of truncated frames, thereby reducing the complexity of the protocol and simplifying the allocation algorithm for scheduling the resource pools.

Furthermore, the actual coverage distance and edge demodulation performance of the candidate proposal are not degraded, and its uplink and downlink timeslot allocation ratio are more suitable for the business characteristics of small-granularity uplink sensing and measurement collection and downlink control data packets in the electric power industry. Therefore, compared with proposals 1 and 2, the overall performance of the candidate proposal is superior, which can better meet the demand of low-latency control businesses in the electric power industry.

C. MASSIVE DISCRETE CARRIER AGGREGATION

Compared to 4G/5G commercial public cellular networks, the number of aggregated carriers in EP-WPN is large, up to 278 carriers, which poses a higher challenge in intermediate-frequency filter design. An illustration of the massive discrete carrier aggregation is shown in Fig. 7.

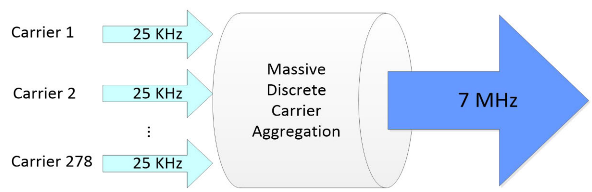

FIGURE 7. An illustration of massive discrete carrier aggregation for EP-WPN.

As the 278 carriers are all within the 230 MHz frequency band, in order to perform intermediate frequency processing more efficiently, for transmission processing, the individual low-speed baseband signal of 25 kHz carriers can be processed by digital upconversion and frequency shift to become a high-speed intermediate frequency signal. Subsequently, multiple intermediate frequency signals are added together to synthesize a broadband signal covering a bandwidth of 12 MHz, which is transmitted through a radio frequency unit after digital-to-analog conversion [15]. According to the candidate proposal in the previous section, the intermediate-frequency design goals are listed in the Table 10.

As shown in Fig. 8, the intermediate-frequency transmitter data link adopts a two-stage digital filtering, interpolation, and mixing structure to up-convert the baseband signal of each frequency carrier into an intermediate-frequency signal, and then adds up to synthesize a wideband intermediate-frequency signal [9].

The 278 authorized 25KHz carriers in the 230MHz band are divided into two clusters, that is, the first cluster is 223-226MHz containing 119 carriers, and the second cluster is 229-233MHz containing 159 carriers.

The first stage of upconversion uses 278 independent low-pass filters (LPF), cascaded integrator comb filter

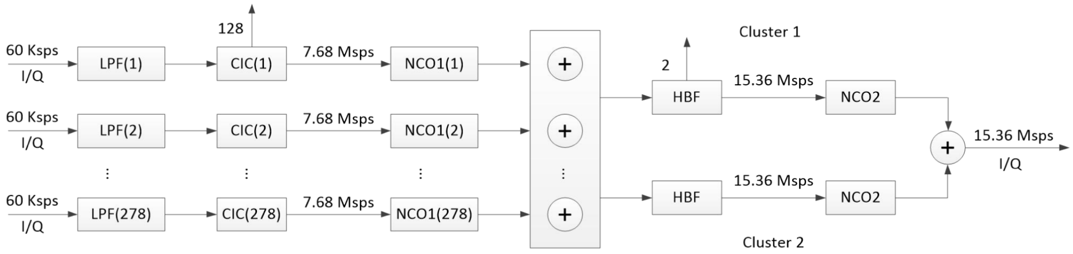

FIGURE 8. The intermediate frequency procedure for EP-WPN transmitter.

TABLE 10. Design Goals of Intermediate Frequency.

Intermediate Frequency Parameter	Value
Number of I/Q Channels	278
Input Sampling Rate	60Ksps
Output Sampling Rate	15.36Msps
Processing Latency	0.5ms
Filter Passband Bandwidth	11.25kHz
Filter Cutoff band	12.5kHz
Passband Flatness	<0.02dB
Out-of-band Suppression	50dB
Carrier Space	25kHz
Frequency Adjustable Range	+/- 7.68MHz

(CIC) and numerical controlled oscillator (NCO1) to aggregate 278 discrete carriers into two clusters. The output of 278 NCO1 is divided into two groups through software configuration, and the outputs within each group are added together to form two clusters [32]. The second stage of upconversion uses two independent half band filter(HBF) and numerical controlled oscillator to achieve the aggregation of two clusters into a single 15.36MHz intermediate frequency signal.

1) LOW PASS FILTER

The low pass filter(LPF) is the first stage of digital upconversion, and as a pulse shaping filter, it limits the bandwidth of the baseband signal and eliminates the inter-symbol interference. The LPF ensures flatness of the passband signal while maximizing the attenuation of the transitional and stopband signals. In order to achieve the coexistence of EP-WPN and traditional 230 MHz digital radio, according to the digital radio specifications [2], the out-of-band suppression must reach 65 dB. However, considering that the OFDM baseband signal itself has no noise interference between the subcarriers and fades in the sideband, the stopband suppression of the LPF only needs to reach 50 dB. The LPF conduct a regular finite impulse response digital filter (FIR) design with a maximum configurable order of 241, a default passband bandwidth of 11.25 kHz, a stopband bandwidth of 12.5 kHz, a ripple coefficient of 0.02 dB, and a stopband suppression of 70 dB. The LPF coefficients are quantized in 18 bits, and the coefficients are symmetric and configurable. Therefore, each 241-order filtered I/Q data requires only 122 multiplication operations. Considering that the LPF operating clock frequency is 400 times the sampling rate, the time-division multiplexing structure for I/Q data and computing resources can be adopted, requiring only one multiplier and a small number of adders, thus significantly saving circuit resources.

2) CASCADED INTEGRATOR COMB FILTER

A cascaded integrator comb(CIC) filter is an effective interpolation and decimation filter widely used in multi-rate digital signal processing. The CIC transfer function, as in formula (1), consists of an integral part ($H_I^N(z)$) and a comb part ($H_C^N(z)$).

$$H(z) = H_I^N(z)H_C^N(z) = \frac{\left(1 - Z^{-RM}\right)^N}{\left(1 - Z^{-1}\right)^N} \quad (1)$$

In formula (1), N represents the cascade stage, R is the interpolation factor, and M is the difference delay [33]. The first sidelobe suppression of a single-stage CIC is 13.46 dB, and the stopband attenuation is unsatisfactory. In practical applications, cascade configurations of multiple CIC filters are often adopted, but they should not have too many stages as this can increase the distortion within the passband. Based on the characteristics of the CIC filter, it is well suited for narrowband signal interpolation and decimation at a large ratio during digital up-conversion and down-conversion. In the EP-WPN, a three-stage CIC interpolation filter with an interpolation factor of 128 (N=3, R=128, M=1) is used, and its specific structure is shown in Fig. 9.

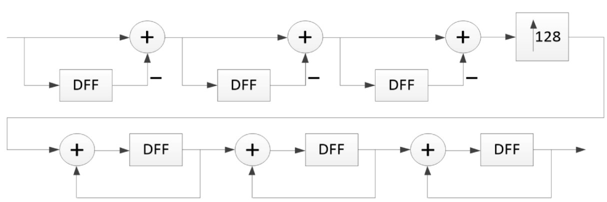

FIGURE 9. The structure of CIC filter.

As can be seen in Fig. 9, the CIC structure is quite simple, consisting of a comb filter, an interpolator, and an integrator, where the comb filter has a sampling rate of 60 ksps, the integrator has a sampling rate of 7.68 Msps, and a 128-fold interpolation is achieved by inserting 127 zeros between adjacent samples.The hardware implementation of CIC can be performed with subtractors, adders, and delay registers (DFF), without multiplication operations, which results in a small circuit area and high processing speed.

Passband attenuation is one of the main drawbacks of CIC, which is usually compensated by adding a compensation filter in the time domain.Considering that the bandwidth of a single carrier in EP-WPN is very narrow, with small intra-band attenuation, pre-compensation can be performed in the frequency domain (before IFFT) for each subcarrier amplitude when necessary, and there are only six effective subcarriers in each carrier with low computational complexity. Therefore, no passband compensation is performed for the CIC filter in the EP-WPN.

3) NUMERICAL CONTROLLED OSCILLATOR

Suppose the baseband signal is:

$$S(\omega) = I(\omega) + jQ(\omega)$$

Its up-conversion principle is:

$$\begin{aligned} S_I(\omega) &= S_I(\omega) \cdot e^{jw_I} \\ &= I(\omega)\cos(\omega_I)\text{-}Q(\omega)\sin(\omega_I) \\ &\quad + j\left[Q(\omega)\cos(\omega_I) + I(\omega)\sin(\omega_I)\right] \end{aligned} \tag{2}$$

As shown in Fig. 10, up-conversion can be achieved by multiplying the sine-cosine local oscillator signal generated by the NCO after phase accumulation with the transmitted complex baseband signal.

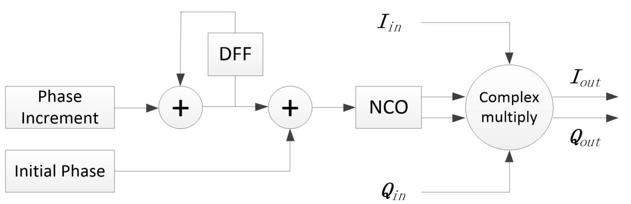

FIGURE 10. The structure of frequency Upconvertion.

The NCO1 and NCO2 working frequencies can be configured in the EP-WPN. In practical applications, adjusting the configuration of NCO1/NCO2 to avoid the frequency occupied by digital radio [34]. Both NCO1 and NCO2 have an accuracy of 25kHz(Δf) and the same implementation structure. NCO1 has a sampling rate of 7.68Msps(Fs), with a phase accumulation bit width of 9bits($2N = Fs/\ \Delta\ f$). NCO2 has a sampling rate of 15.36Msps, and a phase accumulation bit width of 10bits. The sine-cosine waveform of the NCO can be generated using a lookup table or coordinate rotation digital computer (CORDIC). Considering the narrow phase accumulation bit widths of NCO1 and NCO2, it is simpler to use the lookup table, which only needs to store the sine and cosine values within the angle of $\pi/4$. The others can be obtained by looking up the table after sine-cosine transformation or sign transformation. The NCO1 and NCO2 lookup tables have sine and cosine values of 32 and 64, respectively, with a bit width of 16. Complex multiplication in upconversion requires four multiplication operations. Because the working clock frequencies of NCO1 and NCO2 are eight and four times the sampling rate, respectively, only one multiplier is required for each of them by using the time division multiplexing method.

4) HALF BAND FILTER

The half band filter(HBF) is a special FIR filter, whose passband and stopband are symmetrical and have equal widths relative to 1/2 of the Nyquist frequency, and the ripples in the passband and stopband are also equal.The impulse response of the HBF is:

$$h(k) = \begin{cases} 1, & k = 0 \\ 0, & k = \pm 2, \pm 4 \cdots \end{cases} \tag{3}$$

From formula 3, it can be seen that the HBF impulse response value is zero at all even indices except for one at h(0), and compared with the ordinary 2-fold interpolation FIR, the coefficients are symmetric and nearly half of them are zero, which reduces half of the filtering computations when the HBF is used for the conversion of the sampling rate. The HBF is implemented by inserting a sample point of amplitude 0 between adjacent sampling points in the time-domain waveform and then filtering out the high-frequency mirror portion to achieve the transformation of the time- domain inserting 0 to the accurate interpolation value.

In the EP-WPN, the maximum order of the HBF is 25, with a stopband attenuation of 78 dB. The coefficients are quantized in 16 bits and symmetrical for center tapping (1/2), with only six effective coefficients and six multiplication operations. The HBF operating clock frequency is eight times the input sampling rate, and can be implemented by the time-division multiplexing method, with only one multiplier needed for each of the I/Q channels.

By adopting the above digital processing method, the computational load of digital intermediate-frequency operations can be significantly reduced, realizing the aggregation application of large-scale discrete carriers. The signal receiver process is the inverse of the transmitter process, achieving high suppression of adjacent channel interference between each carrier.

D. SPECTRUM SENSING AND INTERFERENCE AVOIDING

The interference received by the EP-WPN mainly includes broadband full-frequency interference, narrowband co-channel interference, and narrowband adjacent-channel interference. Broadband full-frequency interference is mainly caused by various light-emitting-diode(LED) electronic screens, electronic billboards, electronic nameplates, and neon lights, with electromagnetic radiation ranging from 200MHz to 600MHz, but the attenuation is fast. After the wireless devices are 30-50 meters away from the neon lights, the interference of the neon lights can be ignored. Narrowband co-channel or adjacent-channel interference mainly comes from high-power data digital radios that occupy certain carriers in 230 MHz frequency band.

The EP-WPN employs spectrum sensing technology to avoid interference and to schedule and allocate carrier resources more efficiently [11]. Spectrum sensing is essentially to measure the carriers and report the measurement results. The base station determines whether the measured carrier is being interfered, and how to avoid using the interfered carrier based on the measurement results and other algorithms. For carrier measurement, it is necessary to support the measurement across the full bandwidth range, and the measurement result feedback granularity should be at the level of each carrier, to avoid interfering carriers accurately.

The terminal can be configured to measure carriers in two ways. In the first method, the carrier measured by the terminal is not specified, and the terminal reports the measurement result of the cell reference signal according to its implementation [12]. This method is mainly used to judge the large-scale fading condition of the terminal and to assist the base station in assigning the appropriate number of aggregated carriers, modulation type and coding rate, repetition times, etc.. In the second method, the terminal is specified to measure one or more carriers, and reports the independent measurement results of each measured carrier. This method is mainly used to accurately determine the carriers that suffer from fixed long-term interference.

The basic spectrum detection algorithm can be categorized into two types according to the detection strategy: single-carrier spectrum detection schemes and multi-carrier spectrum detection schemes. The former detects each carrier channel individually and determines whether the channel is occupied by a specific criterion, for example, an energy detection algorithm or a matched filter algorithm. The latter compares all carrier channels simultaneously to determine the occupied channel. Compared to the single-carrier spectrum detection scheme, the multi-carrier scheme can compare multiple channels and has less dependence on noise variance information, resulting in better detection performance.

The EP-WPN can adopt a combination of multiple spectrum detection algorithms, and the specific algorithms do not need to be standardized. A two-stage dual-threshold spectrum sensing algorithm is proposed in [35]. The algorithm divides the energy space into three regions, uses different spectral sensing algorithms in different energy regions, and dynamically adjusts the threshold according to the noise uncertainty. In [13], a multi-scale wavelet transform spectral null sensing method based on a covariance matrix is proposed, which is considered to have better detection performance at low signal-to-noise ratios than traditional energy detection methods.

The EP-WPN also adopts frequency hopping (FH) technology to combat time-varying frequency selective fading, by which the currently interfered carrier of the terminal is quickly adjusted to other carriers, thus obtaining frequency diversity gain, as illustrated in Fig. 11. Through the combination of carrier sensing and frequency hopping, the EP-WPN can effectively cope with various narrowband interferences. The granularity of terminal measurement and reporting can be accurate for a single carrier, and the measurement range is the full bandwidth. Therefore, the base station can obtain the interference situation on each carrier of the full bandwidth and remove the long-term interfered carriers from the frequency-hopping resource pool, which can resist long-term interference on a certain carrier or some carriers. Random frequency hopping within the frequency-hopping resource pool effectively resists short-term and random interference.

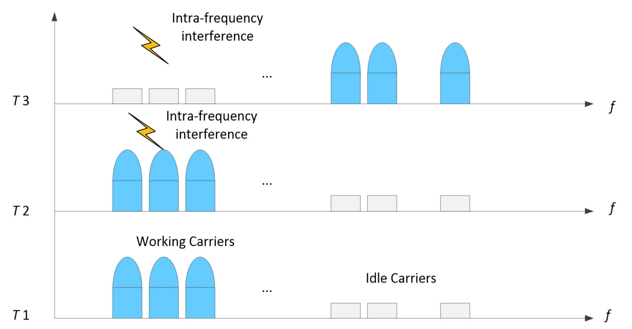

FIGURE 11. An illustration of frequency hopping.

E. STACK ISSUES

In the stack design of the EP-WPN, we fully draw on the protocol stack design of 4G/5G, and conduct targeted optimization design based on the characteristics of the electric power businesses.

1) MULTI-CARRIER TRANSMISSION

The EP-WPN supports multi-carrier scheduling and single-carrier multi-frame transmission to meet the requirements of various electric power businesses and services. For precise control and power distribution businesses, frequency domain resources are prioritized for scheduling, using more carrier resources to enhance transmission reliability and minimize latency. For information acquisition and monitoring business, to achieve wide-area low-power access, the frequency domain preferably uses a single carrier and improves reliability by scheduling multiple frames and supporting multiple repetitions.

For multi-carrier scheduling, the carrier pool of a cell is divided into a common carrier area and a traffic carrier area. The common carrier area is mainly used for terminal's initial access. Control channels and service channels can both be beared on multiple carriers, and different service terminals can be configured to occupy different service carrier areas.

2) LOW POWER WIDE ACCESS

For electric power business and application scenarios, EP-WPN can provide wide-area coverage for rural distribution and utility networks, with a maximum cell coverage radius of 30Km and a signal coupling loss of 155dB. To meet the requirements of low-power long-range wireless access (LPWA), EP-WPN adopts various technologies, such as deep sleep, repeated transmission, and energy spectral density enhancement, to achieve low power consumption and deep coverage over long distances.

Deep sleep Technology: The terminal operates in an energy-saving mode during the transmission gap, when the terminal is attached to network, but there is no signaling or data transmission. The terminal enters a deep-sleep state to minimize power consumption.

Time diversity technology: The same data signal is retransmitted multiple times according to the configured time slot interval; thus, the diversity gain is obtained to enhance the coverage performance. At the same time, the coverage area is divided into different coverage levels according to the strength of the network-transmitted signal, and the network configures terminals with different retransmission times based on the coverage level of the terminal according to the area where it is located.

Energy Spectral Density Enhancement: The terminal transmits narrow-band signals, thus enhancing the power spectral density, which can effectively improve the coverage gain of the signals. The minimum frequency unit of the EP-WPN is 25 kHz, which has a power spectral density gain of 8.6dB compared with the cellular 4G public network. The control and service information for both uplink and downlink transmissions can be sent within a narrower bandwidth, thereby reducing the demodulation requirements of the receiver and increasing the coverage distance.

Multi-frame joint transmission: Through time-domain multi-frame joint transmission and frequency-domain multi-subband multiplexing, the coding rate is further reduced and the system receiver sensitivity is improved. This facilitates the adaptive transmission of control and traffic channels, and improves the control reliability of edge users. The network can configure different transmission frame numbers according to radio channel variations, ensuring spectral efficiency, while improving coverage range.

3) RADIO RESOURCE CONTROL STATE

Because of the different characteristics of various power businesses and drawing on the design of public commercial cellular networks, EP-WPN adopts three states of radio resource control(RRC) to meet the requirements: IDLE, RRC Connected, and RRC Inactive, as shown in Fig. 12. For electric power businesses with low latency requirements such as precise control and power distribution, the terminal is permanently in the RRC connected state after being attached to the network, with real-time always online, without the need for random access prior to data transmission, ensuring transmission latency. For information acquisition and monitoring businesses with large latency requirements and high power consumption requirements, the terminal enters the RRC idle state or even the power saving mode(PSM) state when there is no data transmission, saving air interface resources and improving resource utilization. For different latency requirements and power-saving levels, different extended discontinuous reception(eDRX) and PSM parameters were configured.

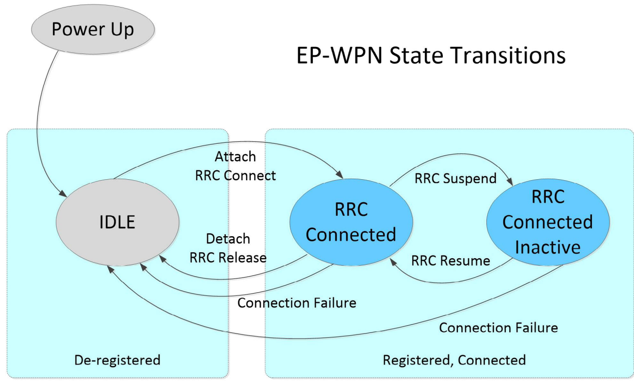

FIGURE 12. **RRC state transitions of EP-WPN.**

4) HEADER COMPRESSION

The EP-WPN stack utilizes a fully Internet Protocol(IP) data transmission method. The data length of the existing control and acquisition business in the smart grid is relatively short, resulting in a large proportion of IP header overhead. To decrease the excessive overhead caused by IP headers, IP, User Datagram Protocol(UDP), and Real-time Transport Protocol(RTP) headers are compressed. The Packet Data Convergence Protocol(PDCP) sublayer of the EP-WPN stack effectively performs header compression on the IP packets submitted by the upper layer, compressing the IP, UDP, and RTP headers to a byte in length, thereby improving the channel efficiency and validity of the packet data, ensuring the transmission of more effective data content within limited frequency band resources.

5) CONTROL PART

Owing to the importance of electric power business data, the EP-WPN has been further enhanced in the control part compared with the public network.

To ensure the security and confidentiality of electric power control data, the EP-WPN employs a multi-layer security mechanism. In the network layer, encryption and integrity protection are applied to both the access layer and non-access layer. In the service layer, dedicated chip-level hardware encryption processing for the electric power industry is utilized, and different security access gateways and forward and reverse isolation devices are employed for different service partitions. For electric power equipment, the device's MAC address is bound to the SIM ID of the communication user, and the accessed end-to-end slicing tunnel is restricted, to resist external intrusion and false network spoofing attacks.

In terms of control architecture, the EP-WPN adopts a tree-shaped centralized three-level topology, which is divided into access points, edge agent points, and core control points. This is consistent with the three-level network architecture

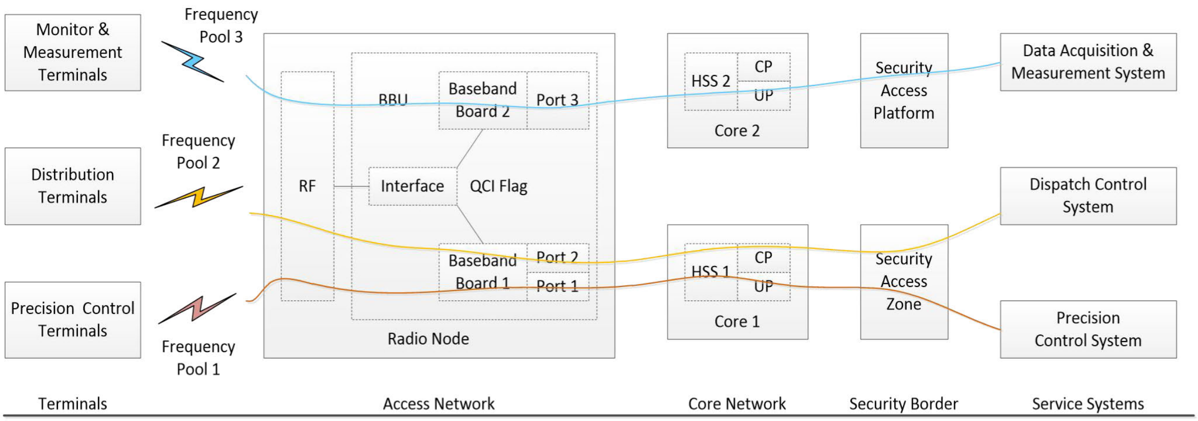

FIGURE 13. A diagram of channel isolation for EP-WPN.

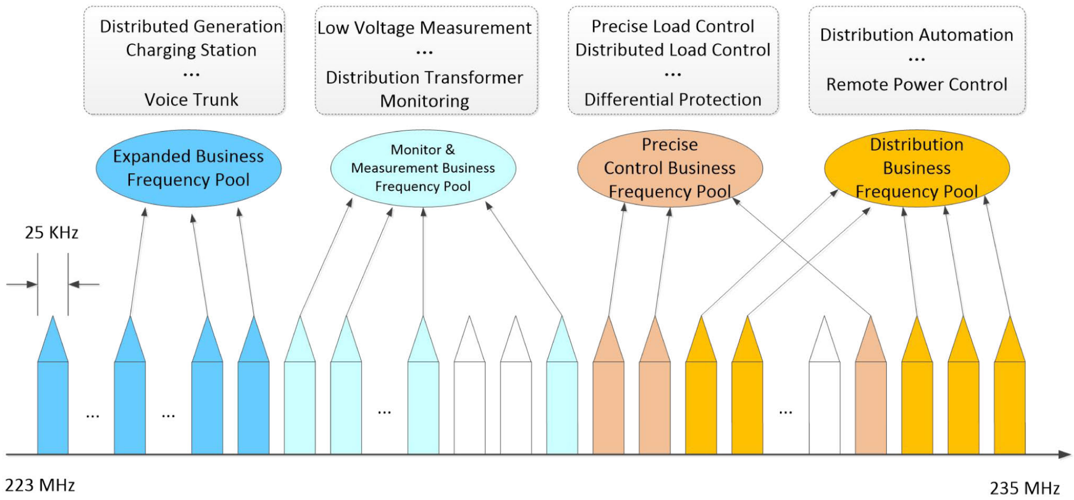

FIGURE 14. An illustration of frequency pool planning for different power services.

of "high voltage - medium voltage - low voltage" in the power grid. This approach allows for a perfect match between communication information flow and energy flow, enabling a deeper integration of information flow, energy flow, and business flow. On the other hand, wireless public networks are primarily focused on consumer services and adopt a two-level network architecture of access network and core network.

6) SLICE AND SECURITY ISOLATION

Various electric power business terminals access to the EP-WPN, and different electric power business scenarios have different requirements for network security, mobility, latency, and reliability. Therefore, it is necessary to adopt network slicing technology to divide a physical EP-WPN network into multiple virtual networks, each of which is allocated to different electric power business scenarios with logical isolation and independence from each other.

For power grid application scenarios, network slicing not only isolates service data but also improves data security. Compared with the "soft" slicing of the wireless public network, a stricter "hard" slicing technology can be adopted [7], which not only requires adjustments to the network architecture, but also requires more accurate identification of service data, from the framework of the network architecture to the end-to-end flow of different service data, from the planning and using of radio frequency to the partitioning of the core network, and from channel isolation to the division of hardware processing boards, all of which need to be designed in detail.

The security isolation design strictly abides by the principle of "security zoning, network dedication, horizontal isolation and vertical authentication", and the base station provides dedicated channels for specific power businesses through independent time-frequency resources and transmission boards or ports to meet the physical isolation requirements of different services in different power security zones, as shown in Fig. 13.

The EP-WPN supports QoS classification identification(QCI). When a user signs up, the core network system sets the priority information and stores it in the Home Subscriber

Server(HSS), and the base station synchronously caches the relevant information in the HSS. When the base station receives uplink data from the terminal, it compares the terminal ID number with the cached information to determine the priority and service type of the terminal. It also sets the QCI for a specific flag bit in the subsequent message frame of the terminal, which is used for the selection of subsequent processing boards and isolation channels.

The transmission channels between the base station and core network are categorized into precise load control channels, power distribution automation channels, and other acquisition channels according to the type of business [16].

The EP-WPN core network system is divided into an exclusive core network for the management information zone and an exclusive core network for the production control zone, in accordance with the requirements of power grid security protection. The core network for the production control zone is subdivided into different hardware modules for precise load control and non-precise load control processing. The various partitions are isolated from each other and the corresponding processing resources can be adjusted as needed.

The radio frequency between the base station and terminal is divided into multiple frequency pools according to the type of electric power business to achieve frequency or carrier isolation. Frequency pool planning overcomes the continuous carrier limitation and optimizes carrier selection based on spectrum sensing for critical businesses. The frequency pool division is shown in Fig. 14.

IV. OPEN ISSUES AND FUTURE RESEARCH

The electric power and communications industries have not yet discussed the new features and functions of EP-WPN Release 2. In terms of its vision, the EP-WPN should be able to fully meet the objectives of Section II, including ultra-low latency (less than 20ms) for differential protection of power distribution, larger system capacity and user numbers, massive access of distributed photovoltaic control terminals, and precise load control terminals. The EP-WPN will achieve network autonomy through endogenous intelligence capability, demonstrating a digital twin mirror of network management that is free of manual maintenance. Therefore, there are still many technical issues and challenges, as shown in Fig. 15, and a preliminary discussion of future research directions is presented below.

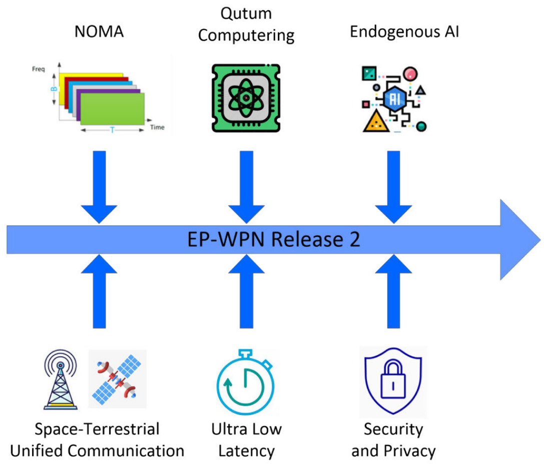

FIGURE 15. Key challenges of EP-WPN release 2.

A. NON-ORTHOGONAL MULTIPLE ACCESS

Non-orthogonal multiple access (NOMA) can effectively support multiple users to transmit simultaneously on the same time-frequency-space resource [10], thereby improving the system throughput and terminal connection amount. It can be theoretically proven that NOMA achieves the capacity boundary of multi-user systems. The new multiple access technology also includes random access, which can operate in both scheduled and unscheduled scenarios without user identification.

For power sensing acquisition and monitoring services, massive access based on non-orthogonal multiple access can significantly increase the terminal density, providing strong support for the EP-WPN's low power consumption and ultra-large-scale connection scenarios. This will serve as a fundamental physical layer technology to be studied during EP-WPN Release 2.

B. ULTRA LOW LATENCY

For ultra-low latency smart grid businesses, such as power distribution differential protection with 20ms requirement, or wide-area distributed load control services, EP-WPN Release 2 will further optimize the system design in various aspects to reduce transmission latency [36].

In terms of network architecture, the architecture will be optimized in combination with the service master station and sub-station, and edge computing and edge caching technologies will be deployed, so that the distributed decision-making, processing, and storage resources are as close as possible to the terminal equipment. Distributed direct communication between terminals is supported to reduce communication delays and data round-transmission time.

In terms of network protocol stack, optimization and improvement of the protocol design will be conducted by simplifying protocol stack complexity, adopting lightweight protocols, and reducing the protocol hierarchy to reduce protocol processing and transmission delay.

In terms of wireless air interface numerology and parameters, a shorter frame structure can be considered in time domain to reduce the scheduling transmission interval. In frequency domain, a larger subcarrier spacing can be used to shorten the symbol duration, and new waveforms, such as Generalized Frequency Division Multiplexing or Filter Bank Multi-Carrier (GFDM/FBMC), can be used to accelerate the side-band signal attenuation between carriers. In [8], the authors proposed a method of multiple carrier adaptive aggregation and variable FFT length by spectrum sensing and interference measurement of individual carriers, which can improve bandwidth utilization to 96%.

C. QUANTUM COMPUTERING

Quantum information technology includes quantum computing and quantum communication technology and can achieve absolute secure communication [37]. Quantum computing utilizes the superposition and entanglement of quantum states to perform information processing [38], which has the most significant advantage of ‘‘parallel operation’’, and can achieve extremely large-scale computation in a short time compared to existing computing paradigms. Quantum communication utilizes the information transfer function of quantum media for communication [39], which includes quantum key distribution, quantum teleportation, and other technologies.

In EP-WPN Release 2, new features, such as endogenous intelligence, will result in a large number of cloud-edge-terminal collaborative computing. In smart grids, the adoption of quantum computing enables parallel large-scale computing, effectively reducing power consumption and supporting the implementation of real-time digital twins.

D. SPACE-TERRESTRIAL UNIFIED NETWORK

EP-WPN Release 1 is limited to ground-based communication. However, in remote and mountainous regions, specifically along extra-high-voltage power transmission corridors, geographical constraints significantly inflate the cost of deploying EP-WPN. Consequently, the adoption of space-based satellite communication access in these areas is deemed more economically viable.

EP-WPN Release 2 will support the integration of space-based and terrestrial communication technology [40], and the terminal adopts unified air interface access technology, which can adaptively switch to ground or satellite access. This is not only meaningful for remote areas, but also helpful for conventional regions. During normal times, dual-link adaptive transmission enhances communication reliability, and during disaster emergencies, the airspace link acts as a reliable communication backup method to effectively support the dispatching and control of the power grid.

E. ENDOGENOUS AI AND AUTONOMOUS NETWORK

The EP-WPN is mainly used for electric power communication, and operation personnel in the electric power industry lack professional experience in communication operations and maintenance. Therefore, EP-WPN release 2 will have endogenous intelligence and network autonomy capabilities, building an integrated intelligent management platform to achieve intelligence, automation, and self-optimization of various network configurations, network control, and network performance without manual operation.

The integrated intelligent management platform will adopt artificial intelligence and digital twin technology to conduct deduction and prediction of the operational situation of EP-WPN in digital space [41], and promptly feed back the prediction results to the physical network. Subsequently, in combination with the new state of the physical network, it will conduct a new round of iteration and optimization in the digital space. The integrated intelligent management platform supports unified orchestration [42], global scheduling [43], and coordinated control of integrated space-terrestrial communication resources [29], enabling seamless and smooth switching between different communication modes. It supports configuration management, online status and performance monitoring, and remote version upgrading of communication terminals, network equipment, and edge computing devices. It also supports self-configuration of heterogeneous networks and self-optimization of network performance [44], avoiding relying on professional manual configuration and optimization with high technical thresholds.

Processed by endogenous AI algorithms, the EP-WPN is equipped with network autonomy, capable of autonomously accomplishing intelligent real-time scheduling of communication resources [45], autonomous planning and intelligent decision-making, service level agreement guarantee, self-configuration and self-optimization dynamic correction of mobility, interference coordination, network load, and other functions. Through online real-time monitoring of the operational status of the communication network, real-time extraction of operational indicators, and utilization of cutting-edge digital technologies such as deep learning and big data mining [46], full-dimensional intelligent analysis of massive network management data will be conducted, to achieve dynamic adaptive change in network topology, operational risk early warning, alarm identification and fault diagnosis.

F. SECURITY AND PRIVACY

The access of massive sensing terminals to smart grids in every link of the power grid business has resulted in an exponential increase in computation of security encryption and trusted authentication, posing significant challenges to EP-WPN and security access gateways for service main stations. Further, privacy issues related to socialized distributed photovoltaic power generation need to be considered.

The EP-WPN supports heterogeneously distributed security architectures. In [47], the authors discussed the application of blockchain technology in the power IoT and concluded that blockchain technology can significantly improve the security of distributed communication. In [31], the authors analyzed the taxonomy of attacks on the wireless physical layer and proposed a lightweight optimized protection algorithm to enhance the efficiency of wireless security for production automation. The smart grids will establish a complete holographic digital space for electric power; therefore, it is necessary to continue to study and optimize the security architecture and algorithms of the EP-WPN in terms of confidentiality and privacy.

V. CONCLUSION

With the promotion and development of China’s ‘‘Carbon Peak and Carbon Neutrality’’ strategy, a large number of distributed power generators are connected to the power grid, and generation-grid-load-storage needs to achieve real-time interaction and large-scale control, which presents a revolutionary evolution requirement for EP-WPN. Through the gradual evolution of EP-WPN functions in different releases, the EP-WPN will ultimately support the construction of a sustainable power communication infrastructure in terms of throughput, latency, quality of service, intelligence, heterogeneous integration, and security. This paper provides a comprehensive overview of EP-WPN, introduces the development history of EP-WPN, proposes the design objectives and time plan of EP-WPN in combination with the characteristics of the electric power businesses, and focuses on describing the system design and basic key technologies of EP-WPN that are different from commercial public networks, including its distinguishing features of frame structure and numerology, massive carrier aggregation and intermediate frequency processing, spectrum sensing and interference avoidance, and protocol stack design. Then future technological directions for the next EP-WPN evolutionary development are prospected, including non-orthogonal multiple access, ultra-low latency, quantum computing, space-terrestrial integration, and endogenous intelligence. Currently, some researchers have presented locally optimized technical proposals based on the 230MHz dedicated frequency band for the electric power industry, such as narrowband trunked communication and low-power IoT communication. However, compared with our proposed optimized EP-WPN technical solutions, these proposals still have some drawbacks in terms of bandwidth, user rates, network capacity, transmission delay, edge computing, and scalability. Although there are still many difficulties in these cutting-edge technologies for EP-WPN, we believe that the demands of the power business will drive the technology to continuously overcome these difficulties, and finally form an EP-WPN solution that can bear the massive control access of the new type power system in the future. Finally, we hope that this article can provide useful inspiration for future research on EP-WPN technology.

REFERENCES

[1] *General Specification for Radio Data Transmission Transceiver*, Standard GB/T 16611-2017, China National Standard, 2017.

[2] *230 MHz Discrete Multi-Carrier Electric Wireless Communication System—Part1: General Technology Requirement*, Standard Q/GDW 11806.1-2018, State Grid Corp. China Standard, 2018.

[3] *General Specification for Data Transceiver*, Standard GB/T 16611-1996, 1996.

[4] L. X. Yang, K. A. Hou, C. Gong, and H. P. Ding, "The application of TD-LTE230M wireless power broadband network technology in smart power-stealing prevention system," *Appl. Mech. Mater.*, vols. 738–739, pp. 1217–1220, Mar. 2015.

[5] Y. Zhong, H. Wang, and B. Chen, "Research on application principles of communication technologies in smart distribution network," *Electr. Power Inf. Technol.*, vol. 11, no. 5, pp. 43–47, May 2013.

[6] L. Zhong, M. Shi, Y. Yu, J. Gu, and M. Shen, "Research and exploratory related to LTE-G 230 power wireless communication special network," *Rural Electrific.*, vol. 40, no. 2, pp. 47–51, Feb. 2020.

[7] H. Zhu and Z. Yang, "Research on the security of a new power wireless private network based on the 230 MHz frequency band," *China Standardization*, vol. 23, no. 16, pp. 241–242, Aug. 2019.

[8] X. Zhao, J. Bai, G. Ding, and L. Xiang, "Optimization of 230 MHz electric power wireless communication technology," *Telcommunication Sci.*, vol. 35, no. 9, pp. 158–164, Sep. 2019.

[9] C. Zhou, Z. Zhou, L. Wang, X. Feng, and X. Tang, "Design of a digital IF transmitter for LTE 230," *Electron. Des. Eng.*, vol. 26, no. 6, pp. 114–119, Jun. 2018.

[10] W. Zheng, J. Chu, and Z. Cheng, "Study of power wireless private network technology based on non-orthogonal multiple access," *ZheJiang Electr. Power*, vol. 39, no. 11, pp. 22–27, Nov. 2020.

[11] M. Yang, "Spectrum hole sensing technology for 230 MHz power wireless private network," *J. Beijing Inf. Sci. Technol. Univ.*, vol. 35, no. 2, pp. 73–78, Apr. 2020.

[12] J. Tong, Q. You, and C. Sun, "Research on interference avoidance strategy in 230 MHz power wireless private network," *Electr. Power Inf. Commun. Technol.*, vol. 18, no. 3, pp. 27–33, Mar. 2020.

[13] J. Wang, D. Zhao, Y. Yuan, M. Mao, and J. Qin, "Spectrum detection based software defined radio in power private wireless network," *Appl. Electron. Technique*, vol. 43, no. 4, pp. 102–106, Apr. 2017.

[14] C. Zhang, L. Zhang, D. Wang, and X. Sun, "Joint detection algorithms for signal in power wireless private network," *Electr. Power Inf. Commun. Technol.*, vol. 18, no. 7, pp. 14–19, Jul. 2020.

[15] Y. Wang, Q. Wu, Z. Zhang, X. Liao, and S. Deng, "Design and simulation for smart meters antenna in 230 MHz power wireless private network," *Electr. Power Inf. Commun. Technol.*, vol. 17, no. 7, pp. 1–5, Jul. 2019.

[16] J. Yao, L. Wei, and J. Guo, "Architecture design of power wireless private network based on resource partition," *J. Global Energy Interconnection*, vol. 1, no. 5, pp. 589–593, Nov. 2018.

[17] X. Chen, F. Yang, J. Liu, and H. Nie, "Research on optimization of 230 MHz electric power wireless private network," *HuNan Electr. Power*, vol. 40, no. 6, pp. 36–39, Dec. 2020.

[18] *Technical Guide for on-Line Monitoring System of Transformation Equipment*, Standard Q/GDW 534-2010, State Grid Corp. China Standard, 2010.

[19] *Technical Specification for Operation Monitoring System of Electric Vehicle Charging/Battery Swap Station*, Standard Q/GDW 10488-2021, State Grid Corp. China Standard, 2021.

[20] *Power User Electric Energy Data Acquire System Functional Specification*, Standard Q/GDW 1373-2013, State Grid Corp. China Standard, 2013.

[21] *Technical Specification for Integrated Indoor and Outdoor Inspection Robot in Substations*, Standard Q/GDW 12012-2019, State Grid Corp. China Standard, 2019.

[22] *Echnical Guide for Autonomous Patrol Inspection of Unmanned Aerial Vehicles for Overhead Transmission Lines*, Standard Q/GDW 12223-2022, State Grid Corp. China Standard, 2022.

[23] *Technical Specification of Demand Response System for Power Load Aggregation Service Provider*, Standard DL/T 1759-2017, Power Ind. Standard, 2017.

[24] *General Requirements for Integrated Energy Custody Service*, Standard Q/GDW 12263-2022, State Grid Corp. China Standard, 2022.

[25] *Technical Guide for Distribution Automation*, Standard Q/GDW 1382-2013, State Grid Corp. China Standard, 2013.

[26] *Dispatching Automation Systems for Distric Power Networks*, Standard GB/T 13730-2002, China Nat. Standard, 2002.

[27] *Technology Specifications for Network Terminal Boundary Admission Management Control in Management Information Area*, Standard Q/GDW 11984-2019, State Grid Corp. China Standard, 2019.

[28] *General Requirement for Electric Wireless Private Network—Part2: Requirement Specification*, Standard Q/GDW 11803.2-2018, State Grid Corp. China Standard, 2018.

[29] *Technical Guidelines for Conception Planning of Electric Wireless Private Network*, Standard Q/GDW 11664-2017, State Grid Corp. China Standard, 2017.

[30] H. Wu, Z. Zhang, C. Guan, K. Wolter, and M. Xu, "Collaborate edge and cloud computing with distributed deep learning for smart city Internet of Things," *IEEE Internet Things J.*, vol. 7, no. 9, pp. 8099–8110, Sep. 2020.

[31] P. Angueira, I. Val, J. Montalbán, Ó. Seijo, E. Iradier, P. S. Fontaneda, L. Fanari, and A. Arriola, "A survey of physical layer techniques for secure wireless communications in industry," *IEEE Commun. Surveys Tuts.*, vol. 24, no. 2, pp. 810–838, 2nd Quart., 2022.

[32] M. Fang, "An intermediate frequency signal processing device and method based on LTE230," Patent CN 104 768 190 B, Aug. 17, 2018.

[33] S. Haykin, *Adaptive Filter Theory*, 5th ed. London, U.K.: Pearson, 2014, pp. 350–360.

[34] Y. Gao, Y. Yin, W. Jia, and B. Chi, "A reconfigurable digital intermediate frequency module for software defined radio transmitters," in *Proc. 12th IEEE Int. Conf. Solid-State Integr. Circuit Technol. (ICSICT)*, Guilin, China, Oct. 2014, pp. 1–3.

[35] J. Cao and J. Liu, "A two-stage double-threshold local spectrum sensing algorithm research forthe power private communication network," *Proc. CSEE*, vol. 35, no. 10, pp. 2471–2479, May 2015.
[36] D. Van Huynh, S. R. Khosravirad, A. Masaracchia, O. A. Dobre, and T. Q. Duong, "Edge intelligence-based ultra-reliable and low-latency communications for digital twin-enabled metaverse," *IEEE Wireless Commun. Lett.*, vol. 11, no. 8, pp. 1733–1737, Aug. 2022.
[37] A. Singh, K. Dev, H. Siljak, H. D. Joshi, and M. Magarini, "Quantum internet—Applications, functionalities, enabling technologies, challenges, and research directions," *IEEE Commun. Surveys Tuts.*, vol. 23, no. 4, pp. 2218–2247, 4th Quart., 2021.
[38] A. S. Cacciapuoti, M. Caleffi, F. Tafuri, F. S. Cataliotti, S. Gherardini, and G. Bianchi, "Quantum internet: Networking challenges in distributed quantum computing," *IEEE Netw.*, vol. 34, no. 1, pp. 137–143, Jan. 2020.
[39] N. Yu, C.-Y. Lai, and L. Zhou, "Protocols for packet quantum network intercommunication," *IEEE Trans. Quantum Eng.*, vol. 2, pp. 1–9, 2021.
[40] O. Markovitz and M. Segal, "Advanced routing algorithms for low orbit satellite constellations," in *Proc. IEEE Int. Conf. Commun.*, Jun. 2021, pp. 1–6.
[41] Y. Dai and Y. Zhang, "Adaptive digital twin for vehicular edge computing and networks," *J. Commun. Inf. Netw.*, vol. 7, no. 1, pp. 48–59, Mar. 2022.
[42] *The Specification and Test Specification of Equipment Management System Northbound Interface of Terminal Communication Access Network—Part2: Wireless Private Network*, Standard Q/GDW 11949.2-2018, State Grid Corp. China Standard, 2018.
[43] T. Chen, X. Zhang, M. You, G. Zheng, and S. Lambotharan, "A GNN-based supervised learning framework for resource allocation in wireless IoT networks," *IEEE Internet Things J.*, vol. 9, no. 3, pp. 1712–1724, Feb. 2022.
[44] Q. Zhang, Y.-C. Liang, and H. V. Poor, "Intelligent user association for symbiotic radio networks using deep reinforcement learning," *IEEE Trans. Wireless Commun.*, vol. 19, no. 7, pp. 4535–4548, Jul. 2020.
[45] M. Eisen and A. Ribeiro, "Optimal wireless resource allocation with random edge graph neural networks," *IEEE Trans. Signal Process.*, vol. 68, pp. 2977–2991, 2020.
[46] C. Zhang, P. Patras, and H. Haddadi, "Deep learning in mobile and wireless networking: A survey," *IEEE Commun. Surveys Tuts.*, vol. 21, no. 3, pp. 2224–2287, 3rd Quart., 2019.
[47] D. Wang, X. Zhao, J. Bai, Q. Wu, and W. Wang, "An study on the application of blockchain based 5G technology in the power IoT," in *Proc. Int. Conf. Power Grid Syst. Green Energy (PGSGE)*, 2021, vol. 252, no. 01032, pp. 1–6.

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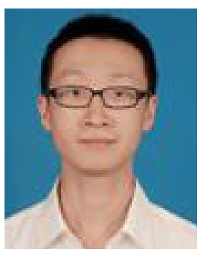

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