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Architecture and Performance Analysis of Wireless Transmission Systems for Smart Grids

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Abstract. One of the most prominent research topics of the modern day is smart grids. Scholars have noted that this has been the case as wireless transmission systems are increasingly being used at the expense of wired transmission systems, with the ever-evolving technology. However, even now, wireless transmission systems still have a number of issues and problems that remain unsolved. Thus, the paper logically conducts the theoretical research on the foundations of smart grids with the example of orthogonal frequency division multiplexing (OFDM) technology, and correctly clarifies how wireless transmission systems are formed. The wireless transmission system architecture is then built, with the layered communication within it. The COVID operation of the cloud layer, pipeline layer, edge layer as well and terminal layer combine together to transmit grid data. Lastly is a comparison between the wired and wireless transmission, where wired transmission has high stability and is resistant to interference, with high costs of construction. Although wireless transmission has a smaller transmission range and efficiency that depends on the surrounding environmental conditions, it has a lower construction cost and a higher degree of flexibility in topographic variety or temporary conditions. Therefore, a future change is the 6G, which involves the integration of non-terrestrial (satellites) networks, with ground-based systems that will be used to proceduralize wireless transmission. It is now broadening its capabilities and horizons in an effort to realize global coverage.

Keywords: Smart Grid, Wireless Transmission, Wired Transmission

1. Introduction

In the modern world, smart grids are closely connected to the lives of people. Along with the development of smart grids and power systems, the shortcomings of traditional wired transmission, with its ineptitude in flexibility, high deployment, and maintenance expenses, and vulnerabilities to both environmental and physical disasters, are becoming more visible. Being flexible in its deployment, having manageable costs, and high levels of adjustability, the wireless transmission systems have slowly become an appropriate solution [1].

As such, the research paper will apply the theoretical analysis, system architecture design, and comparative approaches in the analysis of challenges in the wireless transmission of smart grids and

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the generation of the optimisation strategies. It is meant to provide a strong theoretical base for the future use and development of the wireless transmission systems in smart grids.

2. Theoretical foundation analysis

2.1. Fundamental concepts and components of smart grids

The Smart grids can attain intelligent, automated, and interconnected operation at every level of power production, transmission, distribution, and consumption based on advanced communications, computing, and control technologies. Their fundamental goals lie in the substantial improvement of the efficiency of operations, reliability of supplies, security defences, and sustainability of the environment of power systems [2].

The smart grid entails several elements. The generation segment includes the generation of clean energy, like wind and solar power generation, besides the traditional generators. Within the transmission and distribution part, long-distance power transmission involves high voltage lines, and the other parts involve distribution that provides power to the end-users. In the user and energy storage segment, smart meters are able to provide a two-way flow of information between the grid and the consumers. Demand response mechanisms are elasticity adjustments of the user consumption in accordance with the supply-demand dynamics, and the energy storage facilities are efficient in storing electrical energy. Also, there has been the introduction of a monitoring and control system. Phasor measurement units are installed at the crucial points in the grid to monitor the real-time operational stability of the grid. The technology of Satellite assistance leads to the ability to communicate and monitor areas widely.

2.2. Composition of the wireless transmission system

The wireless transmission system signal transmission architecture includes the multi-carrier and the single-carrier architecture. The Orthogonal Frequency Division Multiplexing (OFDM) is an effective multi-carrier transmission design. The time-domain signals represent the end result of the steps carried out at the transmitter; the frequency data symbols to be transmitted are transformed into time-domain signals using an Inverse Fast Fourier Transform (IFFT), and this signal is then emitted by the antenna. When the signal goes over the wireless channel, the channel effects that the signal is exposed to are multipath fading and noise interference. When the receiver gets the time-domain signal, it uses a Fast Fourier Transform (FFT) to demodulate the signal and re-capture it in the frequency domain to demodulate the data symbols maintained by the signal on each subcarrier. Taking advantage of the orthogonality of the subcarriers, the receiver is made to isolate the subchannels with accuracy, thus reconstructing the original information accurately again [3]. A simplified flowchart of OFDM transmission is shown in Figure 1.

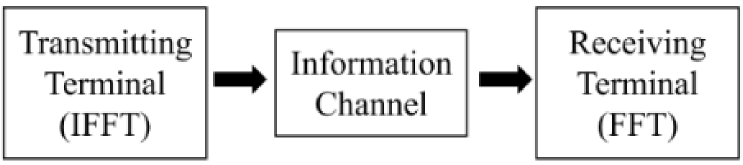

Figure 1. OFDM transmission process (original)

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2.3. Typical wireless transmission technologies

Low Power Wide Area Networks (LPWAN) in typical wireless transmission technologies denote a category of technology custom-made for the Internet of Things (IoT). They strive to compensate for the trade-off by focusing on long-range communication and low power consumption. The LoRa is one of these that is grown and used in this discipline on a large scale [4]. It trades long-range transmission, low power consumption, and strong resistance to interference by mechanisms such as chirp spread spectrum modulation and forward error correction. It provides distances of communication of more than 15 kilometres in the suburbs, and metre ranges of coverage in the urban environment [5]. Its modules are able to run on reception currents of less than 10mA and have deep sleeps, thus greatly increasing battery life [5]. Additionally, working in an unlicensed Sub-GHz frequency license, LoRa has greater flexibility in deployment and reduced the cost of devices, having built common technical standards and industrial environment [5]. These merits imply that LoRa has been used in various IoT applications that require high power, long-range, and dependability, which may include smart metering, vehicle tracking, smart agriculture, smart cities, etc [6].

The LoRa technology has been currently utilized all over the world. As an example, it is seen used in smart agriculture studies in Italy, fire early warning in forests in Spain, and irrigation in Australia, which is water-saving. In China, with the impetus of the China LoRa Application Alliance (CLAA), more than 5,000 LoRa smoke detectors have been installed in the Tongzhou district of Beijing to provide fire early warning, and in Shanghai to provide smart water meters and monitor municipal facilities. It is also important in other situations, like massive agricultural irrigation and monitoring of industrial equipment.

3. Architecture of smart grid wireless transmission systems

3.1. Overall architecture - typical architecture diagram

The efficient and stable operation of smart grids is based on the use of reliable, real-time, and safe communication networks. A simplified architecture design of a smart grid wireless communication system is shown in Figure 2 and consists mostly of the cloud layer, pipeline layer, edge layer, and terminal layer. These layers interoperate to ensure data transmission.

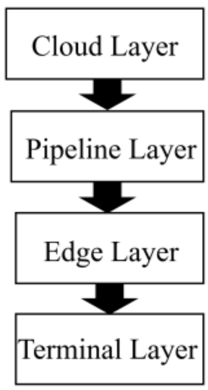

Figure 2. Layered communication architecture diagram (original)

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3.2. Layered communication

All devices that make up the lower layers are primarily monitored, controlled, data collected, and analyzed by the cloud layer, to allow intelligent grid scheduling and management. The SCADA system is a combination of various communication protocols, as the all-important connection between field grid equipment and upper-level dispatch systems. It is responsible for real-time data acquisition and operational status feedback on devices such as smart meters and remote terminal units, and data support to the situational awareness and closed-loop control of the entire grid [7].

The wireless wide-area networks (WLANs), wireless local-area networks (LANs), and wireless personal-area networks (PANs) make up the major part of the pipeline layer. There are dedicated Power wireless networks and public wireless networks. In the case of a wireless personal area network, Zhang Pengxiang came up with an efficient IoT communication system for smart homes. The essential novelty of it is the combination of adaptive Mesh and Cluster Tree network design. It provides high-reliability, low-latency cross-platform networking through a three-layer closed-loop design that includes topology control, protocol stack, and performance optimization to work well with communication among smart home devices [8].

The edge layer acts as an intermediary, and it gathers information on all terminal devices in its range and puts the information on initial processing and conversion before passing the same to the main station over high-speed wireless networks. Distribution Automation Terminals (DTUs) are commonly installed within distribution rooms (or on utility poles) to facilitate such functions as scheduled collecting of data, storage, display, organizing, and transmission [9].

The terminal layer is directly linked to other devices in the physical world, which acquire the data and run commands. The potential solution to the problem is a multi-channel variable-delay down-conversion full-duplex variable positioning approach proposed by Zhang Jingbo with the support of the NB-IoT technology, which facilitates intelligent remote centralized automatic meter reading in low-voltage power systems [10]. In this technology, data are collected using fiber optic sensor nodes and take advantage of NB-IoT features that have a wide coverage area, use minimal power, and offer capabilities of massive connectivity to transmit information over a long distance. Tests reveal that there was only a loss of 5 percent in the transmission of data over long distances. In the case of metric measurements, reading and data acquisition were as fast as 48 milliseconds. This would solve the poor efficiency, high cost, and low levels of accuracy of the conventional manual-based meter reading, which greatly helps in the automation and intelligent control of power system meter reading processes [10].

4. Wireless transmission vs. wired transmission

4.1. Transmission distance

Wired transmission is based on physical media (e.g., fiber optic cables, coaxial cables) to transmit the signals, where the transmission range is limited by the media and methods of signal amplification. Fiber optic cables, being the mainstream wired medium, can be used at transmission distances of tens of kilometers without repeaters (e.g., single-mode fiber has a typical range of 20100km). Cascading through repeater equipment, communication can be spread over a region or even a continent. The total transmission distance has good controllability and stability, and is barely affected by outside environmental interference [11].

The tools of wireless transmission technology are based on the mobility of the electromagnetic waves in space. It has been established in the literature of MIMO wireless transmission that

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conventional methods of single-antenna wireless transmission are susceptible to multipath effects and electromagnetic interference, which usually have shorter ranges (i.e., WiFi technology typically only has a coverage radius of 100 meters, whereas Bluetooth technology is only 10 meters). Even high-tech wireless network like 5G is limited: Macro base stations have a range of about 300 meters to 1 kilometer, and there are even shorter ranges in the millimeter 5G band (less than 100 meters). Despite the ability of multi-base station networks to increase their coverage, due to the nature of propagation of electromagnetic waves, long-distance transmission stability is inferior to wired technologies [12].

4.2. Transmission efficiency

The efficiency of wired transmission technologies is an asset of low loss and low resistance to interference of physical media. The transmission of optical fibers has very low attenuation of signals (about 0.2 dB/km in single-mode fiber) and is not affected by electromagnetic interference or weather conditions. The error rates in the data transmission may decrease to less than 10 -12, and the efficiency of transmission may be reduced to theoretical values. This is especially appropriate in high-capacity, high-bandwidth data transmission calls (like data exchange in the backbone network) [11].

Wireless transmission is very flexible and easily deployable; mobile users may use it and form a network quickly. It is an important part of emergency communications, the Internet of Things (IoT), and mobile internet applications. Nevertheless, channel environments and technical implementations limit its effectiveness. Even though MIMO technology is more efficient due to the existence of multi-antenna variety and multi-path multiplexing, wireless channels are afflicted by multipath fading and noise interlude, leading to the fast decrease in signals and the presence of quite high error rates of bits per message (usually 10-6-10-9).5G is more efficient by use of Massive MIMO and ultra-dense networking, but still is limited by the nature of frequency bands (e.g. high attenuation rates and low penetration at higher frequencies). Within the wired transmission, the overall transmission efficiency is higher than in the wired transmission, and efficiency degradation increases with the transmission distance [12].

4.3. Construction costs

The expenses of wired transmission technologies focus on physical media and implementation engineering. Physical media such as fiber optics and cable are intrinsically expensive, and construction must include excavation and laying of lines (e.g., laying an underground network in a city, building tunnels across rivers/mountains, and so on). The initial construction cost is expensive and the time to build is long; however, maintenance is lower after deployment (long media life, localization of faults is easy) and the final consequence provides excellent long-term cost-efficiency [11].

The fundamental expenses of the wireless transmission technologies are the base station construction and equipment research and development. MIMO technology involves multi-antenna hardware and signal processing software, thus costing more heavily on base station equipment [12]. The use of new wireless-related technologies, such as 5G, will require large numbers of deployed macro and small cells (base density 3-5 times higher in cases of ultra-dense network coverage). First, equipment costs and costs are high, and the continuous investment made in maintenance is mandatory (e.g., power supply in base stations, signal optimization). Nonetheless, the lack of physical medium deployment provides better construction flexibility compared to wired technology

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in very complex topography (e.g., mountains, water bodies) or in cases of temporary requirement (e.g., emergency communications), inexpensive to deploy in specialty settings [13].

4.4. Future outlook

The detailed analysis of wired and wireless transmission technologies has shown that, whereas the use of wireless transmission technologies, such as fifth-generation (5G) systems, has proven to be extremely flexible in complex terrain deployment and temporary deployment because of the absence of a physical medium, they are still limited by the propagation properties of electromagnetic waves. Such limitations are a lack of stability to support long-distance transmission, reduced efficiency as the distance increases, and high deployment and maintenance costs. Communication technology is poised to through all these bottlenecks to render way up to other enhanced forms of global seamless connectivity by developing 6G networks that are more deep-seated to reach such advanced application scenarios as ubiquitous mobile ultra-broadband (uMUB), ultra-high data density (uHDD), and ultra-high-speed, ultra-reliable, low-latency communication (uHURLLC) [14, 15]. Nevertheless, with limited geographical coverage, deployment capabilities, and scalability of terrestrial base stations, existing 5G networks cannot satisfy the bandwidth and latency limits and stability of such applications in distant and oceanic regions. In response to this, non-terrestrial networks (NTNs), especially highly sophisticated satellite constellations, are becoming essential solutions [16]. Satellite networks complement Earth systems by providing a high throughput capability, low latency, and multiple geographical areas, enabling them to bypass geographical and economic limitations. This forms the platform for the global integrated connectivity shared by 6G and the next level of wireless communications directed towards integrated air-space-ground convergence [16].

5. Conclusion

The paper objectively investigates the structure of smart grids and their wireless transmission system, builds a sample architecture diagram, and provides a layered analysis of their communications. Thereafter, it contrasts the wireless and wired transmission techniques with regard to three aspects, which include the distance of transmission, energy consumption, and the cost of construction. The wired transmission shows such obvious benefits in fixed communication aspects in the long range, where there is greater stability and efficiency than the other. However, wireless transmission is more skilled in flexibility, mobility, as well as speedy implementation. Lastly, it is possible to discuss the shortcomings of 5G, on which the paper suggests that 6G will be a metamethod of redefining ground coverage with an extensive intelligent connection composed of air, land, and space, and communication speeds that are much faster. With a thorough combination of non-terrestrial networks such as satellite with the ground system, future wireless communications have a chance that will eliminate the limitations of distance as well as the limitations of financial situation. This will facilitate credible, effective international coverage, which will form a strong base of connectivity to the digital transformation of the economies and societies.

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