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State-of-the-Art of Ad Hoc/Sensor Networks for Ophthalmic Devices: Communication and Energy Efficiency

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ABSTRACT

To meet the challenges of ophthalmic disease diagnosis and treatment, ophthalmic implants/wearable devices have great potential in continuous monitoring and intelligent diagnosis and treatment. This article focuses on the communication protocols and energy-efficient design of self-organizing networks in such devices, aiming to overcome stringent constraints such as miniaturization, biosafety, ultra-low power consumption, and dynamic communication. The content covers physical layer characteristics, MAC layer and routing layer optimization, network security mechanisms, and energy-saving strategies such as wireless power supply, low-power hardware, intelligent power management, efficient data processing, and cross-layer collaboration. Looking to the future, intelligence, energy self-sufficiency, biosafety, multifunctional integration, and standardization are the main trends and challenges, and multidisciplinary cross-innovation is urgently needed to promote technological development and improve visual health.

KEYWORDS

Ophthalmic devices; Ad hoc/sensor networks; Energy efficiency; Communication protocols; Biosafety

1 Introduction

Visual health is crucial to quality of life. However, the diagnosis and treatment of various ophthalmic diseases such as glaucoma and diabetic eye complications still face challenges [1]. Traditional intermittent diagnosis in hospitals is difficult to capture the dynamics of the disease, and it is difficult for doctors to continuously monitor ocular physiological indicators, making early intervention difficult. Therefore, the development of new technologies that can achieve continuous physiological monitoring is crucial to improving early warning, personalized treatment and long-term management of eye diseases.

In recent years, ophthalmic wearable/implantable devices represented by smart contact lenses and intraocular implants have shown great potential [1-3]. These miniaturized devices directly interact with the ocular surface or intraocular environment, making it possible to continuously, non-invasively or minimally invasively obtain key biomarkers such as intraocular pressure (IOP) and tear glucose, thereby achieving accurate and convenient management of diseases such as glaucoma and diabetes [1, 3]. In the future, intelligent integrated ophthalmic devices that integrate sensing, diagnosis and on-demand treatment functions will be an important development direction [3].

Such advanced functions, especially in complex systems with multi-node collaboration, are highly dependent on effective inter-device communication and self-organizing network technologies. Ad hoc/Sensor Networks provide a basic framework for building these ophthalmic micro-intelligent systems because they do not require fixed infrastructure and support dynamic networking and distributed collaboration [3]. However, the application of self-organizing networks in the special environment of ophthalmology faces severe challenges stemming from the equipment itself (such as miniaturization, biocompatibility, power consumption) and the application scenarios (such as channel dynamics, data security), which will be discussed in detail in subsequent chapters.

In view of this, this review focuses on systematically reviewing the latest technical progress in communication protocols and energy-efficient design of ad hoc/Sensor Networks for next-generation ophthalmic implants/wearable devices. This article aims to sort out the key technologies, emerging trends, and open issues to be solved in this field, and provide a reference for related research. The subsequent chapters are arranged as follows: Chapter 2 will outline the basic characteristics and requirements of ad hoc networks in ophthalmic application scenarios. Chapter 3 and Chapter 4 will review the latest progress and core technologies of communication protocols and energy-efficient design, respectively. Chapter 5 will discuss future trends and open research issues in this field. Finally, Chapter 6 will summarize the whole paper.

2 Self-organizing networks in ophthalmic implants/wearable devices: foundations and characteristics

Ophthalmic implants and wearable self-organizing networks are designed to provide data support for continuous diagnosis and personalized treatment of diseases by monitoring key physiological parameters such as intraocular pressure (IOP), tear glucose, and temperature [1, 3]. These applications impose unique and strict constraints on network design: although the amount of single-shot data is small, continuous monitoring requires high reliability and acceptable latency in data transmission, and the data is usually low-rate but has extremely high integrity requirements [4]. Considering the energy storage limitations brought about by device miniaturization and the high energy consumption of communication modules, network protocol design must focus on maximizing energy efficiency [4]. The thermal effects generated by communication electronic devices and RF radiation must be controlled at extremely low levels to avoid damaging eye tissue, which imposes strict restrictions on transceiver power and communication duty cycle [4]. The rapid changes in wireless channels caused by physiological activities such as eye movements require sufficient robustness of the communication link [4]. At the same time, the transmitted physiological data involves patient privacy, and the network needs to provide effective lightweight security mechanisms to defend against attacks and avoid additional energy consumption [5].

In order to cope with these extremely resource-constrained and dynamic environments, clustering is considered a key technology to improve network scalability, energy efficiency, and manageability [6]. The architecture organizes nodes into clusters, which are coordinated by cluster heads (CHs). It balances network energy consumption and prolongs network life through intelligent elections (e.g., based on residual energy and location information, and can be optimized using heuristic algorithms such as the improved grey wolf optimizer [7]) and periodic rotation of CHs [6]. Its typical features include: ordinary sensor nodes (SNs) sense physiological parameters and transmit data to CHs, which are responsible for data collection and initial aggregation, and then converge to an external base station (BS) or a personal smart terminal through a single hop or multiple hops. The hierarchical topology and node division of labor [6]; the network needs to have the ability to dynamically form and maintain clusters and adaptively adjust to node movement or failure to cope with link changes caused by ocular physiological activities [6]; the data flow is mainly in the uplink direction from SNs to CHs and then to BS, but it also needs to support a small amount of downlink control signaling [6]. Although the clustering principle in wireless sensor networks (WSNs) can be borrowed, the extreme constraints of ophthalmic applications require targeted adaptation and innovation of the network architecture.

3 Latest developments in communication protocols for ophthalmic applications

For self-organizing networks for ophthalmic applications, the design of the physical layer and the understanding of channel characteristics are the cornerstones for building efficient and reliable communication links and directly affect the performance of higher-layer protocols. The primary challenge comes from the extreme miniaturization requirements of the device, which makes the design of the antenna and its RF front-end circuit extremely difficult. The reduction of antenna size is usually accompanied by a significant decrease in radiation efficiency and an increase in impedance matching difficulty, which also puts higher requirements on overall power consumption control [3]. Secondly, the selection of materials used in ocular implants or wearable devices is extremely stringent. Not only do they require excellent RF properties, but they also need to meet the core requirements of biocompatibility (such as non-toxicity, non-irritation, and anti-biological adhesion) and optical transparency (especially for corneal contact lens-type or intraocular implant-type devices). For example, the study explored the use of emerging materials such as graphene and silver nanowires (AgNW) to make transparent and flexible antennas, aiming to balance the electromagnetic performance of the antenna with the requirements of biomedical applications, while ensuring that it can maintain acceptable RF performance under actual physiological conditions [3].

The complex biological tissue environment in or around the eye constitutes a unique wireless channel. The high-water content of ocular tissues (such as vitreous body and aqueous humor) causes significant absorption loss of electromagnetic waves during propagation, resulting in severe signal attenuation. In addition, the curved surface structure of the eyeball itself, the dynamic changes of the tear film, and the periodic movement of the eyelids (such as blinking, rapid eye saccades, or smooth pursuit movements) all introduce complex multipath effects, shadowing effects, and channel time-varying properties. These factors together lead to rapid fluctuations in signal strength, phase distortion, and even connection interruptions, which pose a severe test to the stability and reliability of the communication link, requiring the communication system to have sufficient robustness to cope with these dynamic channel changes [3]. At the same time, out of extreme consideration for the safety of sensitive ocular tissues, the thermal effects generated by radio frequency devices must be strictly controlled within biosafety standards, which means that the specific absorption rate (SAR) must be far below the specified threshold, which directly limits the device's transmit power and antenna design, further exacerbating the difficulty of achieving reliable communication in lossy channels [3].

4 Recent advances in energy-efficient design for ophthalmic applications

At present, the high-energy-efficiency design for ophthalmic implants and wearable self-organizing networks is committed to overcoming the core contradiction between the limited energy storage of micro-devices and the need for long-term continuous operation under the premise of ensuring biosafety. Its key strategy first focuses on the continuous acquisition of energy and the optimization of power consumption at the hardware level: wireless power transmission (WPT) technology, including near-field communication (NFC) and far-field microwave solutions, as well as the exploration of new transparent flexible antenna materials such as graphene and silver nanowires (AgNW) to improve energy collection efficiency and biocompatibility [3], supplemented by research on environmental energy collection technologies such as photovoltaics, temperature differences, and piezoelectricity. At the same time, the use of ultra-low-power microcontrollers (MCUs) and sensor chips with deep sleep modes, optimized RF transceiver design, and refined power consumption management and efficient operation through application-specific integrated circuits (ASICs) or highly integrated systems on chips (SoCs) [3] are the hardware foundation for laying the foundation for system energy efficiency.

The key to achieving extreme energy efficiency lies in intelligent energy consumption management mechanisms and efficient data processing processes. Specific measures include the widespread adoption of mature power management technologies such as duty cycle scheduling and dynamic voltage frequency scaling (DVFS). At the media access control (MAC) layer, collaborative energy saving is achieved by optimizing existing standard protocols (such as IEEE 802.15.6 CSMA/CA [8]) or introducing security mechanisms that can resist malicious attacks (such as selfish attacks targeted by PP-MAC [5]) and thus avoid unnecessary energy waste. In addition, at the data level, data preprocessing (such as filtering, feature extraction) at sensor nodes or cluster heads (CH), applying advanced data compression algorithms, and aggregating and fusing data from multiple nodes in a clustering-based network architecture can significantly reduce the total amount of data that needs to be transmitted through the wireless channel, thereby significantly reducing the energy consumption of the communication link [6-7].

Cross-layer collaborative design is considered to be an effective way to achieve global optimal energy efficiency and break through the optimization bottleneck of a single layer. By comprehensively considering and coordinating the information and control mechanisms of the physical layer, MAC layer, routing layer, and even the application layer, such as dynamically adjusting MAC parameters based on real-time channel quality, incorporating the perception of node energy status and temperature into routing decisions (such as the WETRP protocol [4]), combining efficient network topology control strategies (such as cluster-based routing [6] and intelligent cluster head election algorithms [7]), and taking into account the indirect positive impact of security protection mechanisms on overall energy consumption [5], network performance can be optimized more comprehensively and systematically. This holistic approach helps achieve on-demand services and extreme energy efficiency, thereby better meeting the stringent requirements of ophthalmic applications.

5 Future trends and open research issues

In the future, the development of self-organizing networks in ophthalmology will significantly tend to be more intelligent and adaptive. The core driving force is the deep integration of artificial intelligence/machine learning (AI/ML) technology and communication protocols, including the use of AI/ML to achieve dynamic optimization of MAC layer parameters (such as the improvement of IEEE 802.15.6 CSMA/CA mechanism [8]), more optimized intelligent routing decisions [4, 6, 7], and context-aware networks. At the same time, the exploration of advanced energy solutions remains a core issue, and more research will focus on efficient hybrid energy harvesting and intelligent management (which is an extension of wireless energy transmission technology [3]) and nearly battery-free operation. In addition, while ensuring long-term biosafety and confidentiality of sensitive data, it is crucial to develop enhanced biocompatible and degradable materials [1, 3], build an end-to-end security and privacy protection framework that goes beyond existing specific defense mechanisms (such as PP-MAC [5]), and introduce privacy-enhancing technologies. In terms of standards, as the technology matures, the standardization and interoperability issues for ophthalmic application characteristics (beyond the existing basic standards such as IEEE 802.15.6 [8]) will become increasingly prominent. The core open scientific problem is how to achieve robust, intelligent, and secure wireless communication and network functions under the premise of extreme miniaturization, long-term biosafety, and extreme energy efficiency to support complex multifunctional integration and closed-loop diagnosis and treatment applications, which requires deep cross-disciplinary and collaborative innovation.

6 Conclusion

This paper focuses on the self-organizing sensor networks in the next generation of ophthalmic implants/wearable devices and systematically reviews the core technological progress in communication protocols and energy-efficient design. Such networks provide a key technical path for the continuous monitoring and intelligent diagnosis and treatment of ophthalmic diseases, but they pose great challenges to the stringent requirements of miniaturization, biosafety, ultra-low power consumption, and dynamic reliable communication.

Research shows that the current progress is mainly reflected in the communication protocol level, from the special antenna and channel research of the physical layer [3], to the standardized access and energy efficiency and safety optimization of the MAC layer [5, 8], to the clustering architecture and energy environment perception strategy of the routing layer [4, 6, 7], all of which are trying to adapt to the unique constraints of ophthalmic applications. At the energy-efficient design level, the exploration continues around the two dimensions of "open source" [3] and "saving" [4-8] of energy.

In the future, more research breakthroughs will significantly improve the level of ophthalmic medical care and improve global visual health through deep cross-integration with multiple disciplines such as artificial intelligence, new materials, micro-nano manufacturing, and biomedical engineering.

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