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Wireless Communications for Optogenetics-Based Brain Stimulation: Present Technology and Future Challenges

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The authors present a review of the current technologies that have been proposed for different wireless optogenetics solutions, ranging from devices that are head mounted to miniature devices that can be embedded deep in the brain. They focus on a comparative analysis of the architecture and structure of the devices, the wireless technology used for signaling to the unit, as well as the energy consumption profile for each of the devices.

Abstract

The ability to decipher brain functions and understand the neuronal communication networking properties to develop innovative solutions to treat neurodegenerative diseases remains one of the biggest challenges in biomedicine. Since the early days, numerous solutions have been proposed for BMI, largely concentrating on the use of tethered electrodes that are inserted into the brain to either stimulate or suppress neural activities. In recent years, the field of optogenetics has provided a new alternative of utilizing light to stimulate genetically engineered neurons. While the original approach proposed the use of tethered optical cables inserted into the skull to transfer light into the brain for stimulation, numerous advances have been made to incorporate wireless technologies that will allow these devices to be attached to the skull or implanted in the brain. This article presents a review on the current technologies that have been proposed for different wireless optogenetics solutions, ranging from devices that are head mounted to miniature devices that can be embedded deep in the brain. We focus on a comparative analysis of the architecture and structure of the devices, the wireless technology used for signaling to the unit, as well as the energy consumption profile for each of the devices. Finally, the article presents future challenges to further miniaturize wireless optogenetic devices, concentrating specifically on the communication properties.

Introduction

Neurodegeneration, which is a systematic cause of neuron death, can lead to a number of diseases, including Alzheimer's, Parkinson's, as well as amyotrophic lateral sclerosis. The field of *brain machine interface (BMI)* [1] aims to support patients who suffer from neurodegenerative diseases. The traditional BMI method is based on electrical simulation, which is also known as focal brain stimulation. This method requires implanting electrodes deep into the brain, and is widely used in neuroscience for providing therapeutic effects to patients with epilepsy and Parkinson's disease. A more recent approach is based on optogenetics, which aims to utilize light to stimulate genetically engineered neurons, providing a better option for controlling the cells compared to conventional electrical stimulation [2]. First, it can excite the particular neuron with approximately 10 percent higher precision [2]. Second, for neural activity recording using light stimulation, activity recording can be conducted easily since there is no electromagnetic interference. Third, with light stimulation, the target cells can be restricted only to certain cells that are genetically engineered as opposed to electric stimulation. This provides very fine-grained control of neural circuits, which to date has been a major challenge. Unlike electrical brain stimulation, optogenetics has not yet been clinically tested on the human brain. Recently, Retina Foundation of the Southwest, through the sponsorship of RetroSense Therapeutics, is planning to carry out the first clinical trial on human patients with retinitis pigmentosa.

The early solutions for optogenetics utilized optical fibers that are inserted into the skull to stimulate the neurons, which is impractical for daily use. However, in recent years, thanks to the wireless communications community, advancements have been made by incorporating wireless technologies for optogenetics to make them less invasive [2]. In this article, we review a number of solutions for wireless optogenetics, where we investigate the use of wireless communication for head mountable devices to the more recent approaches of miniaturization that can be embedded into the cortex. Building on this, we provide a number of future challenges for further miniaturization of wireless optogenetics, touching in particular on the challenges for communications as well as other emerging applications.

The article is organized as follows. The next section presents background on optogenetics. Then we present a comprehensive review of current solutions for wireless optogenetics. Following that, we present the future challenges. The final section presents the conclusion.

Background on Optogenetics

Before realizing the full operation of the optogenetic system, the first step is to genetically engineer the neurons by specific transmembrane proteins (*opsins*) (Fig. 1). These proteins include

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Channelrhodopsin 2 (*ChR2*) for triggering action potential, *Halorhodopsin* (*Halo*) for neural activity inhibition, and *Archaerhodopsins* (*Arch*) which hyperpolarizes the neuron (action potential inhibition). The next step is light stimulation. The ChR2 is a light-gated ion channel, which, upon illumination of blue light, will result in the opening of a cation channel that depolarizes the neuron. On the other hand, NpHR (Halo) is a light-controlled pump, which injects chloride ions into the neuron upon yellow light illumination, resulting in an inhibitory effect.

The current choice of optical neurostimulation components are limited to lasers or micro-light emitting diode (μ-LED). Laser and laser diodes require high power consumption, slow warm-up time, high cost, and the use of tethered optical fibers to steer the light. However, they use narrow spectral bandwidth to produce high light intensity with low beam divergence. On the other hand, μ-LED has advantages in terms of wavelength range, low cost, power consumption, stable illumination, compact size, and fast response. The examples of the wavelength range with respect to the required power include blue μ-LED (465 nm) that can deliver 25 mW, while yellow μ-LED (585 nm) can only deliver 3 mW from 200 mm diameter optical fiber. Sufficient power is also required for the μ-LEDs to trigger the optogenetic process. Therefore, a challenge for miniaturization and implantable wireless optogenetics is the ability to harvest the energy or wirelessly transfer the energy.

There are two methods of creating optogenetic construct in animals. First is the transgenic method where animals are bred specifically with optogenetic induced cells. The second is through virus injection for gene therapy to an existing neuron, which is more suitable as long as there is no rejection from the immune system. Another novel method is culturing and engineering in-vitro neurons that can be implanted into the human brains. Currently, the optogenetic applications for humans is being planned for clinical trials in the near future.

Current Developments

Figure 2 illustrates a subset of solutions that we discuss in this section, where we start with head mounted to fully implantable units embedded into the brain or nervous system. The wireless communication technologies used for these solutions include infrared (IR), high frequency/near field communication (HF/NFC), and ultra high frequency (UHF). We evaluate each device with respect to its size, device construction, and wireless technology. The consideration for selecting the appropriate technology includes propagation characteristics in the medium, size of the device, and power sufficiency. Based on this, we provide a comparison in Table 1 between the different wireless optogenetic solutions, including ultrasound, which is part of our proposed system in this article. In terms of signal propagation performance, ultrasound should be considered instead of IR, HF/NFC, and UHF technologies. In parallel, the ultrasound energy has lower attenuation in biological tissues. According to Food and Drug Administration (FDA) regulation, the ultrasound exposure threshold level on the human body is

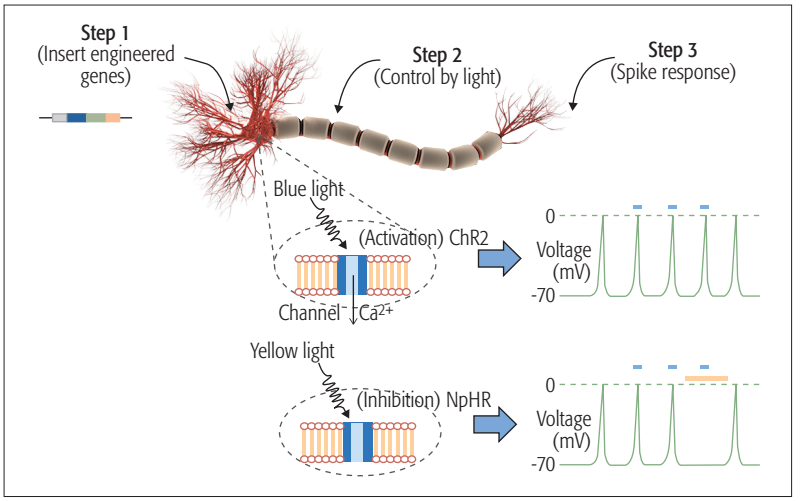

Figure 1. Illustration of wireless optogenetics. Step 1 requires engineered genes to be placed in the neuron. Step 2 illustrates the wireless optogenetic process, where light is emitted onto the neurons that will lead to either stimulation or inhibition (step 3).

720 mW/cm^2, while RF is 10 mW/cm^2. The drawback of ultrasound technology is the manufacturing complexity. As the frequency goes up, the antenna size gets smaller, which makes the usage of both HF and UHF technologies more appealing for device miniaturization. In conclusion, BMI design has to consider specific types of communication for different types of application for superior communication performance.

Wireless Optogenetics Based on Infrared

Wireless Optofluidic Systems:

Device Properties: The device presented in [3], and illustrated in Fig. 2a, combines drug delivery pharmacology and optogenetics stimulation. The drug delivery is through the microfluidic channel that also contains the microscale inorganic light emitting diodes (μ-ILEDs) based on Gallium Nitride (GaN) used for the opto-stimulation. The major novelty of this solution is that the conventional rigid metal cannulas and fiber optics are replaced by four miniature, soft, and flexible microfluidic channels made of 50 mm thick and ~450 μm width *elastomer polydimethylsiloxane* (PDMS) and μ-ILEDs. Each channel has a cross-sectional area of 10 × 10 mm^2. The PDMS material used for the microfluidic channel is so transparent that 95 percent of 400–700 nm wavelength is able to traverse through it.

Energy Management: Two small rechargeable lithium ion batteries are used as the power source. The weight of the battery is approximately 330 mg, and the dimension is 3 × 9 × 10 mm^3 with an operating voltage of 3.6 V.

Communications: The signaling between a base station and a head-mounted receiver using IR is based on 10 ms pulse width with frequencies of 5, 10, 20, and 40 Hz. Since the receiver is programmed to distinguish different activation signal, the head-mounted receiver can have multiple functionalities for releasing certain drugs. While the IR signaling at multiple frequencies provides flexibility in controlling the device, the major disadvantage is the need for line of sight (LoS) communication, which means there should be a clear path between transmitter and receiver.

There are two methods of creating optogenetic construct in animals. First is the transgenic method where animals are bred specifically with optogenetic induced cells. The second is through virus injection for gene therapy to an existing neuron, which is more suitable as long as there is no rejection from the immune system.

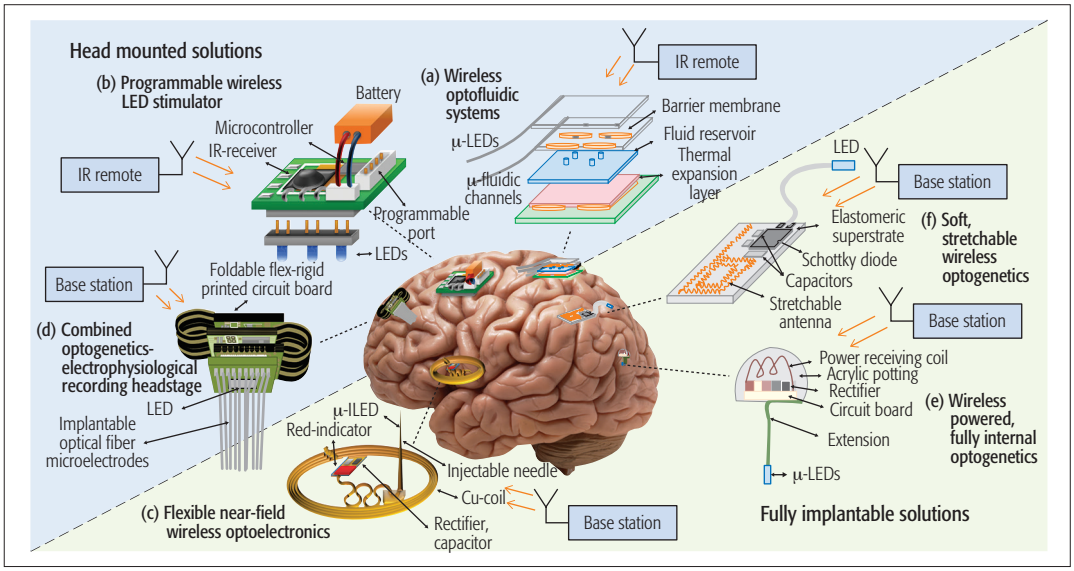

Figure 2. Various solutions for wireless optogenetics illustrating the different scale of the devices, as well as their locations on the brain.

Programmable Wireless LED Stimulator for Optogenetics:

Device Properties: A miniature wireless LED stimulator using multiband infrared and multicode signals was developed in [4] (Fig. 2b). The system comprises three main components, that is, an IR transmitter for the operator to control the desired signals, an LED stimulator mounted on the head and penetrating into the skull, and small LEDs to trigger the action potential on the optogenetic constructs.

Energy Management: The 12 V DC power to operate the IR transmitter is provided through an AC adapter. For the LED stimulator, the power is supplied using a lithium polymer battery whose output is 3.7 V at 10 mAh.

Communications: The IR transmitted signal comprises three components, which include the leader code, an 8-bit binary code, and a stop bit. These 8-bit binary codes consist of 256 unique identifications for each channel. These specific codes are used to identify multiple IR transmitters for crosstalk avoidance between the channels. Furthermore, the IR code can be modulated using amplitude shift keying to carrier frequencies of 30, 38, or 56 kHz, which features multiband transmission.

As for the LED stimulator, 470 nm blue light LED is used to trigger the ChR2 proteins. Here, the received IR signals are decoded by an onboard microcontroller, which converts the 8-bit binary code in order to activate the LED. Using IR instead of RF transmission brings the advantage in terms of weight and complexity in constructing the IR communication system, which also has benefits in terms of cost and power consumption. However, LoS transmission is still required for the IR communication.

Wireless Optogenetics Based on High Frequency

Flexible Near-Field Wireless Optoelectronics:

Device Properties: The device proposed in [5] incorporates a copper coil for power transmission with a surface-mounted chip for control, a capacitor for impedance matching, a rectifier, and a μ-ILED for optogenetic excitation (Fig. 2c). Since the copper coil is put on the surface of the brain, an injectable needle is required to precisely locate the target neurons. The bilayer encapsulation of *Parylene* and *Polydimethylsiloxane* applied on the device ensures stability during operation.

Energy Management: Energy transfer and control signaling are achieved through a combination of the copper coil and a micro-sized chip. The fundamental operation of the coil is based on the passive near field communication (NFC) concept, which utilizes electromagnetic induction. The total size of the coil is 9.8 μm × 60 μm × 18 μm. The optical output power of the device depends on the distance and orientation of the RF generator.

Communications: The NFC frequency of 13.56 MHz can accommodate transmission distance up to 30 cm between the RF generator and the receiver loop antenna. At the same time, multiple antenna operation can be supported using a multiplexer. Based on the voltage-current measurement, the power generated is sufficient to turn on the μ-ILEDs emitting different wavelengths (UV — 390 nm, blue — 470 nm, green — 540 nm, yellow — 580 nm, and red — 650 nm).

Using the NFC approach for both power transfer and optogenetic excitation introduces a cheap and relatively easy avenue toward manufacturing the device. From the propagation loss point of view, the HF band utilization gives lower loss than UHF band. While this design is smaller than other similar designs for BMI applications, the size of the coil (diameter of 9.8 mm) should still be considered for multiple device implementation.

Wireless Optogenetics Based on Ultra High Frequency

Combined Optogenetics and Electrophysiological Recording Wireless Headstage:

Device Properties: The combination of optogenetic stimulator and multichannel electrophysiologcal recording using wireless headstage is proposed in [6], and illustrated in Fig. 2d. This device facilitates both neural activity recording

Wireless technology	Frequency	Pros	Cons
Infrared (IR) [3, 4]	300 GHz–430 THz	Low power consumption; multi-band transmissions.	LoS between base station and implanted unit; requires a battery unit for the head unit.
High frequency (HF) [5]	3–30 MHz	Medium propagation loss in biological tissue; cheap and easy to manufacture; supports energy harvesting circuitry.	Coil dimension of approx. 1 cm; requires surface mounted chip (NFC).
Ultra high frequency (UHF)	300 MHz–3 GHz	Smaller coil diameter than HF circuitry; cheap and easy to manufacture;sSupports energy harvesting circuitry.	High propagation loss in biological tissue.
Ultrasound [9]	≥ 20 kHz	Low propagation loss in biological tissue; size of hundreds of mm; supports energy harvesting circuitry; safe utilization in human tissue.	Complex circuit manufacturing; difficulty in ultrasound frequency addressing.

Table 1. Comparison of different wireless optogenetic solutions.

and optogenetics stimulation. The headstage is composed of two main components, that is, foldable printed circuit board (PCB) and a detachable implanted module. A major issue with this solution is the large head mounted unit, which is impractical for daily use.

Energy Management: The power supply of the headstage unit is fairly bulky and supplied by a 3.7 V, 100 mAh Lithium-ion battery with a weight of 2.1 g, operating for 105 min. As far as stimulation efficiency is concerned, for a 150 mA stimulation current with 10 percent duty cycle at a firing rate of 45 spikes/s, it lasts approximately 70 min.

Communications: The communication for transmitting control signals is from an external base station that operates on the 2.4 GHz frequency. The data rate is reasonably fast, reaching a maximum of 1.4 Mb/s. For the light communication between the LED and the neuron used for the stimulation, this device uses a train of 10 ms pulse width with a current of 150 mA that is used to drive the 465 nm blue LEDs generating 70 mW/mm2 light intensity.

Wireless Powered, Fully Internal Optogenetics:

Device Properties: A fully implantable wireless optogenetic device for stimulating the brain, spinal cord, and peripheral circuits in mice is proposed in [7]. The RF transmitter is in the form of a relatively huge resonant cavity, allowing the animal to freely move. The entire light emitting implant, illustrated in Fig. 2e, weighs around 20–50 mg and has a size of 10–25 mm^3, which is claimed to be substantially smaller than the previous version of wireless optogenetic implants.

Energy Management: In terms of optogenetics stimulation, the μ-LED used in the system has an optimum efficiency (emitted light power/input power) of 19 percent. This power level is sufficient to emit the light power density required for optogenetics excitation, which is 1–20 mW/mm^2. Since the system utilizes a resonant cavity to transmit the energy by resonance inductive coupling, the mouse location interferes with the reception power. However, the center point of the resonant cavity has the highest measurement of light power density, which is approximately 27 mW/mm^2.

Communications: The wireless power transmission consists of a 1.6 mm diameter power receiving coil, while an aluminium resonant cavity (21 cm diameter, 15 cm height) was used as the transmitter. The wireless implant consists of the power receiving coil, rectifier, circuit board, and blue μ-LED. On the transmitter unit, the cavity radiates 1.5 GHz electromagnetic energy to wirelessly power the implant. Considering the propagation of the electromagnetic wave, the implanted device is placed around 3 cm above the resonant cavity, and this includes the floor surface structure in between. Since the system requires a large resonant cavity that radiates RF frequency to transmit power and control the implant, this is only suitable for a controlled lab environment, not for daily use in patients.

Soft, Stretchable, Wireless Optogenetics System:

Device Properties: The optoelectronic systems proposed in [8] utilized the combination of stretchable filaments and a flexible polymer encapsulation, which was embedded into the spinal cord and peripheral nervous system (Fig. 2f). The device comprises four major components: an RF power-harvesting unit, a rectifier, a voltage multiplier, and a cellular-scale 470 nm LED. The durability of the entire unit has been tested by immersing it in 37 °C saline for two months, and for six days in 90 °C supraphysiological temperature saline. Recently, the authors in [10] developed this system including a smaller and lighter implant, and a multichannel antenna to control up to four reservoirs.

Energy Management: The unique design of the RF energy harvester uses a miniaturized stretchable antenna whose total surface area is 3 × 3 mm with an operational frequency of 2.3 GHz and a wide bandwidth of 200 MHz. This wider bandwidth, in comparison to a conventional patch antenna that uses 50 MHz bandwidth, enables the device to harvest more energy. The transmitter antenna from the base station is located outside the body and transmits RF signals to power the device. The configuration of four transmitter antennas can distribute approximately 2 W, which is sufficient for multiple-device activation within 20 cm range.

Communications: The same RF signal used for the energy harvester is also used for control signaling to activate the LED. The LED communicating to the neuron has an optical power density of 10 mW/mm^2, operating at a frequency of 20 Hz with 40 percent duty cycle, and pulse width of 20 ms. Even though the device has been improved by using flexible material compared to a conventional rigid antenna, the size is still considered big for large-scale deployments if they are to be embedded in different parts of the brain. In addi-

A challenge also lies in the optimal scheduling of emitting ultrasound waves for charging from the subdural transceiver to minimize energy depletion, since this device will be embedded under the skull and will also require energy harvesting capabilities on its own (e.g., heat or vibration).

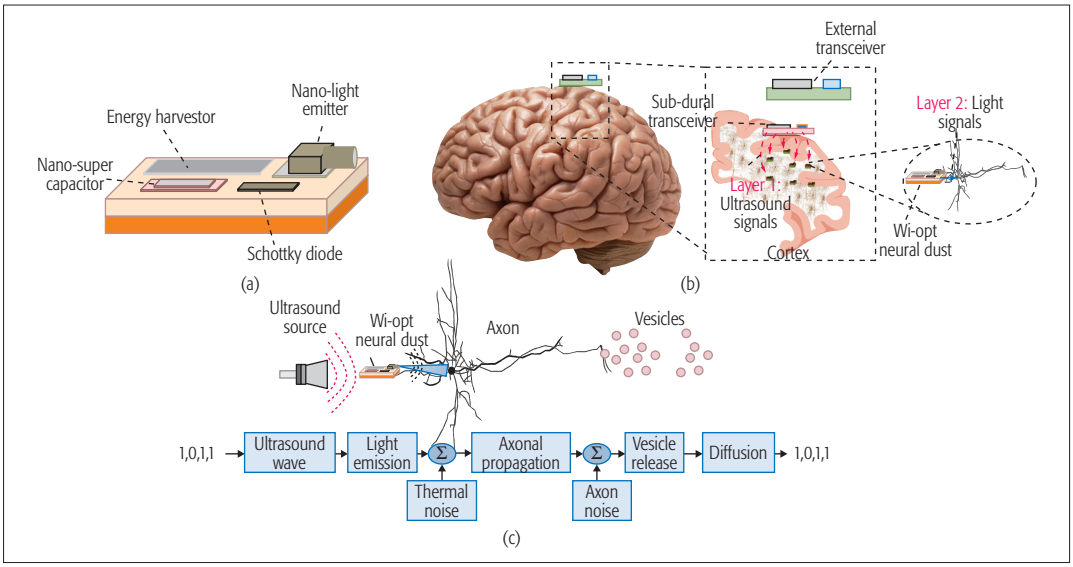

Figure 3. Future miniaturization of wireless optogenetics unit: a) proposed device architecture for a wireless optogenetic nanoscale device; b) insertion of the wireless optogenetic nanoscale device in the cortex (the architecture includes a subdural transceiver that stimulates the device and provides the energy, where this in turn will receive signals from an external transceiver); c) an interface of the wireless optogenetic nanoscale device to a neuron, illustrating the communication blocks from the light communication, to the vesicle release by the neuron.

tion, they can be deformed due to movements and biological strains. This can shift the center frequency to lower values, causing 12 percent coupling efficiency decrease for 30 percent strain in the worst case.

Future Challenges of Miniaturization

The previous section describes developments in miniaturization of wireless optogenetics devices, from head mounted units with implantable optical fiber cables to fully wireless devices that can be embedded in the brain. However, the current solutions are still on the millimeter scale. In order to target long-term deployment into patients, to enable them to pursue a normal active life, further miniaturization is required. Figure 3a illustrates our proposed wireless optogenetic nanoscale device as well as the corresponding components. As illustrated in the figure, energy management will be a major issue, where a nano super-capacitor will be used to store energy that is coming from a harvesting source, such as piezoelectric nanowires [11]. Figure 3b illustrates how these devices can be embedded into the cortex of the brain, and using the architecture from [9], will receive power from a sub-dural transceiver, which in turn will receive power from an external transceiver. The size reduction of the device will minimize the irritation and other side effects on the tissue, such as excessive heating. However, this will result in a number of challenges, in particular from the constraints of the component size, and how this will affect the communication performance. The field of nano communications, which has emerged recently, can play a major role in directing the future evolution toward miniaturization. Figure 3c illustrates the communication representation of a miniature wireless optogenetic nanoscale device stimulating a neuron. In this section, we present the challenges from the perspective of communications.

Communication Challenges

Data Link Layer: The challenge at the data link layer lies mainly in the layer 1 communication for *charging* as well as for *initiating* the device to stimulate light. This may require separate ultrasound beams for each of the two functionalities. The benefit of emitting ultrasound waves for charging is the fact that this could be performed in parallel due to the widespread propagation of the signal that covers all the devices. The schedule for the initiation, however, will be dictated by the required firing patterns of the neuronal networks within the cortex (e.g., specific activities will require a certain pattern of neuron stimulation). Therefore, the scheduling of device initiation will vary and change depending on the user's activities, and this will be controlled by programming into the subdural transceiver. A challenge also lies in the optimal scheduling of emitting ultrasound waves for charging from the subdural transceiver to minimize energy depletion, since this device will be embedded under the skull and will also require energy harvesting capabilities on its own (e.g., heat or vibration).

Physical Layer: While miniaturization causes no significant impact on the layer 1 communication, it will indeed have an impact on the layer 2 light emission propagation for optogenetics stimulation. Although the Gallium Nitride (GaN) μ-LEDs by McCall *et al.* [12] successfully decreased the thickness to only 6.5 mm, there are issues with temperature increase that limit the illumination duration. A major challenge also lies in the light propagation of light from a miniature source to ensure that maximum intensity is applied to the neuron's surface. This is also important due to the blockages that can occur from the soma, axons, and dendrites of neighboring neurons. These components can block the light signal propagation and at the same time lead to excessive reflections, resulting from specular and dif-

fusive scattered propagation. The light reflection from the cell material is also highly dependent on the contents of the cells (e.g., cytoplasm), and the coefficients of absorption and reflections are open research challenges. In [13], a nanoscale plasmonic antenna was proposed for emitting electromagnetic waves in the infrared spectrum. A similar approach can be developed for wireless optogenetics at the nanoscale, which may enable further miniaturization of the device.

Network Layer: One of the challenges in the network layer is addressing of the wireless optogenetic nanoscale devices for the layer 1 ultrasound communication. Due to the minimal computational capabilities, utilizing a bit sequence addressing scheme may not be a viable option, since a processor will be required for the device to process the signals. Integrating the processor will in turn also increase the size of the device. At the same time, a bit sequence of address for each device will also mean that the subdural transceiver will need to emit ultrasound signals for each bit (assuming a simple on-off keying modulation is used where the clocks of all the devices and the subdural transceiver are synchronized), leading to excessive energy depletion. Another option is to use separate piezoelectric crystals that have different resonant frequencies, each corresponding to an address of a device. However, a question remains as to how scalable the network of the wireless optogenetic nanoscale devices will be, given the limited separation of the resonant frequencies between the different types of crystals.

Security Implications: A major issue is the security threats that wireless optogenetics nanonetworks can pose, and in particular if the operation of the devices can be controlled through the external signaling of layer 1. This means that the external transceiver, and possibly the subdural transceiver, will require security countermeasures from misbehaving malicious sources that would like to change the neural stimulation patterns. Since the wireless optogenetic units are below the skull, and will only operate in response to ultrasound signals, this prevents security threats from malicious ultrasound signals. However, a challenge lies in the signaling between the external transceiver and the subdural transceiver. Therefore, the challenge for the external transceiver as well as the subdural transceiver is to be able to recognize signals from malicious devices that aim to get access to stimulating the wireless optogenetic units. The security response must be performed instantly as soon as an attack is performed to minimize any harmful damage that can occur. Although the security threat is a challenge with our proposed miniaturization of wireless optogenetics and its accompanying architecture, the threat also exists with the current implantable solutions. The communication security system on the higher layers (data link and network) is quite robust, since the units are implanted in the brain. The physical access to the unit itself is considerably difficult without surgical procedures to open the cranium. A security breach on this level can only be performed by inserting the intruder unit among the existing implanted units. This requires the opening of the cranium to implant the intruder unit.

Further Challenges

Interfacing to Molecular Communications: The field of molecular communications aims to develop artificial communication systems from biological components. In particular, the Internet of Bio-Nano Things (IoBNT) [14] will interface the artificial molecular communication systems to the Internet, through a bio-cyber interface. The wireless optogenetic unit can represent a bio-cyber interface that enters information into the brain as illustrated in Fig. 3c In this form of communication, the bit transmission will be achieved through light stimulation of neuron that releases the vesicles to communicate to the post-synaptic neuron. The challenge is to engineer the neuron to respond to different light intensity, at the same time having different synthetic circuits within the neuron that can produce varying concentration of vesicle release. The reconnection of the neurons (neuroplasticity) can further add noise into the network. This can affect how digital information is transmitted through the neurons as well as the scheduling sequence of light emission during stimulation.

Nanoscale Dual Stimulation and Recording: An ideal implantable device should incorporate monitoring and recording mechanisms. In [9], experimental validation has shown how the *neural dust mote*, which powers itself through vibrating piezoelectric crystal from an external ultrasound source, is able to monitor the nerve signaling based on back scattering. However, incorporating this into the wireless optogenetic nanoscale devices will be challenging. The current devices do not penetrate through the neuron, but rather emit light externally onto the cell, which implies the lack of a mechanism for sensing the electro-chemical signals propagated through the axon. Alternatively, the usage of electrodes (e.g., optrode, stereotrode, and tetrode microdrives) can measure the signal along the axon. Another solution is to engineer the neurons to emit a genetically encoded fluorescence-based indicator upon stimulation. Using this technique, each device can be incorporated with a molecular imaging module that will capture the stimulation process of the neuron. However, incorporating this may lead to an increase in the size and power requirements of the device.

Ethical Issues: Apart from technical and security challenges, ethical issues are another important issue for BMI, including the field of optogenetics. These ethical issues can be perceived from both personal and social points of view [15]. The patient's consent to access information on their brain functions will be mandatory and a major hurdle due to the fact that this can be categorized as mind reading, and potentially control a body subconsciously. This also includes the optogenetic implementation for humans, which will spark controversy on the use of genetic modification. From a social perspective, the integration between human and machine leads to a liability issue if a misbehaving action is vaguely triggered by either human intention or machine error. Besides this, social interactions between BMI users and ordinary people in certain settings (e.g., competitions) may be questionable in terms of fairness in an individual's capabilities.

The security response must be performed instantly as soon as an attack is performed to minimize any harmful damage that can occur. Although the security threat is a challenge with our proposed miniaturization of wireless optogenetics and its accompanying architecture, the threat also exists with the current implantable solutions.

Realizing the development of wireless optogenetic devices at the nanoscale can be a game changer for future brain machine interface technologies, and at the same time address important challenges for treating neurodegenerative diseases.

Conclusion

The emergence of optogenetics has proven to be an attractive solution for treating neurodegenerative diseases, and numerous advancements have been made in integrating wireless communication technologies to enable the devices to be implanted for long-term applications. In this article we review a number of devices that have been proposed for wireless optogenetics, ranging from larger units that are head mounted with deep insertion into the cortex, all the way to miniature devices that can be implanted in the cortex. While enormous strides have been made in miniaturizing wireless optogenetic devices, to the point that they can be embedded in the brain or the peripheral nervous systems, there still remain numerous challenges going forward into the future. The particular challenges are the ability to scale the devices down to the size of a typical neuron and having these devices interface directly one-to-one for specific types of neurons. Another emerging challenge is the ability to communicate and power these devices, while considering the side effects that can occur to the brain. In this article, we propose an architecture that can realize wireless optogenetic nanoscale devices, where we also discuss the challenges from the perspective of communications. We specifically touch on the challenges at the physical, data link, and network layers, as well as discuss the security implications, and how the new field of nano and molecular communication principles can be incorporated into the design consideration. Realizing the development of wireless optogenetic devices at the nanoscale can be a game changer for future brain machine interface technologies, and at the same time address important challenges for treating neurodegenerative diseases.

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