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Research Article

Interactive Smart Fashion Using User-Oriented Visible Light Communication: *The Case of Modular Strapped Cuffs and Zipper Slider Types*

Jai-Eun Kim,[1] Youn-Hee Kim,[2] Jung-Hun Oh,[1] and Ki-Doo Kim[1]

[1]*Department of Electronics Engineering, Kookmin University, Seoul 02707, Republic of Korea*
[2]*Department of Fashion Design, Kookmin University, Seoul 02707, Republic of Korea*

Correspondence should be addressed to Ki-Doo Kim; kdk@kookmin.ac.kr

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Because LEDs offer flexible expressions such as brightness, color control, and various patterns, they are popularly used in multidevice interactions. Moreover, LEDs have excellent physical characteristics. However, existing LED light-based wearable interactions are designed for interest and attention. So, LED can be used in fashion as it can give new look to our style and at the same time also as an interaction device. Therefore, in this paper, we present the design guideline for regulating the technical implementation, design strategies, and directions of interactive LED devices. The technology and design concepts are demonstrated through a case study (analysis) of an existing LED light-based wearable interaction. We also design a scenario-based iterative collaborative design process model. Finally, we develop a smart fashion of modular strapped cuffs and zipper slider types that can be attached and detached according to the user's preference as the interactive smart fashion using user-oriented visible light communication, ultimately pursuing a visual-MIMO (Multiple-Input Multiple-Output) product through stepwise strategy.

1. Introduction

Wearable technology applied products are now contributing to high value-added businesses that cater to the emotional needs of users seeking creative newness as well as changing consumer lifestyles by fusing technology and fashion. The word "fashion," in this paper, indicates new look of our dress combined with technology. The technology has two purposes: (i) giving our dress a distinctive style and (ii) sharing information about what we want to share. Because of this communication factor, we mention it as "smart fashion" or "interactive smart fashion" or "wearable interactions" or "wearable technology applied products." A good example is smart fashion, which combines clothing with luminous bodies such as optical fibers, LEDs, and electroluminescent films. Smart fashion is being developed for various applications such as entertainment, communication, and safety protection.

The physical characteristics of LEDs are superior to those of other luminous bodies. Specifically, LEDs have long lifetimes and low energy consumptions; moreover, they are more compact, thinner, lighter, and more environmentally friendly than other electronic devices. They react quickly and offer limitless interaction possibilities when combined with various sensors. In addition, the brightness, color, and pattern of LED-based interactions can be freely adjusted. Such flexible expression is ideal for realizing simultaneity in wearable interactions.

Research on light-applied smart fashion is still in the early stage and focuses on attracting the interest and attention of users rather than exploring commercialization possibilities. Current implementations are nonefficient, functionally limited, and cannot establish a social infrastructure. As such, they have failed to gain the understanding and sympathy of people. User-centric smart fashion that is easily accessible and human-friendly demands further research.

To acquire a solid position in the smart fashion market, designers must combine technology with consumer perceptions in the popular market rather than adopt a simple technology-based approach [1]. To this end, we established an interdisciplinary research team of engineers and fashion designers and proposed smart fashion that detects the emotions of consumers and incorporates functionality and aesthetics into the products.

Our interdisciplinary research team has proposed visible light communication (VLC) for wearable interactions (smart fashion) through the following three-stage research strategy: (1) identifying the specialized factors of LED-based visual communication (information visualization) by surveying users; the users' needs then become the evaluation criteria for information visualization; (2) based on the user-needs survey results and the analysis results of interactive smart fashion, proposing design guidelines (technology and design concepts) for technical implementations and design strategies and directions; and (3) designing a process model for the scenario-based interactive collaborative design and developing a smart fashion of modular strapped cuffs and zipper slider types, which can be attached or detached by users. This VLC-based interactive smart fashion is developed via a stepwise strategy.

2. Related Works

VLC is not the latest topic but it has vast application. Visual-MIMO in smart fashion technology is a potential branch of future research. Researchers have tried to implement visual-MIMO in different applications. Corbellini et al. [2] described different user application like home networking, LED-to-LED communication for toys, interactive fashion and fabrics, toys without radio emission, and toy communication with smartphone. They gave an idea about fashion with VLC technology but no proper demonstration. Swartz et al. [3] designed wearable communication system that can control body attached device by personal area networks (PANs) and it has also access to the wide area networks (WANs). Hertleer et al. [4] introduced an intelligent fabric system that contains an antenna operating properly in the 2.4–2.4835-GHz industrial-scientific-medical bandwidth. The similar kind of work was done by Ito et al. [5]. They proposed a wearable jacket to employ endoscope system. Pyattaev et al. [6] showed current and emerging connectivity solutions for high-density wearable deployments, their relative performance, and open communication challenges. Pathak et al. [7] made survey paper on VLC system. They described VLC system components, communication medium for VLC, and the application of the VLC like indoor localization, gesture recognition, screen-camera communication, and vehicular networking.

Except [2], the other studies are about either VLC system or wearable devices for communication. None of them directly worked with both VLC and wearable technology. Reference [2] only mentioned VLC technology for interactive fashion design. We focused on the fusion of "wearable" technology and "LED communication." And we developed the fashionable visual-MIMO prototype using user-oriented visible light communication. In our paper, we show that interactive fashion with VLC is good candidate for future fashion and technology industry.

3. Survey on LED Light for Usability

In interactive smart fashion, the diverse needs of users and the important elements in a usability assessment must be considered. To this end, our interdisciplinary research team conducted a preliminary survey on users' needs, which revealed the important factors reflecting the specialized characteristics of LED-based visual communication and used them as an evaluation scale for information visualization. Thus, users' opinions were actively collected and applied in the initial design stage, and their needs were analyzed through user-centric design approaches. The improvement factors were also identified.

The user-needs survey and analysis revealed three types of needs; infotainment (information + entertainment) communication, nonverbal communication for people with hearing impairments, and a wearable interface with detachable modules. The analysis results are outlined as follows:

(1) Content Survey for Infotainment: a questionnaire based on a 5-point Likert scale was administered to 20 women in their twenties. The survey focused on the content elements needed for interactions. Eighty-five percent of the respondents reported that LED-based visual communication facilitates the sharing of sympathy and enjoyment. That is, most of the respondents desired both functionality and decorativeness of the LED element. Moreover, in the integration of communication devices into interactive fashion, the visual sensory element (the LED) was preferred over the tactile sensory element (vibration) (50% versus 45% of respondents). Forty-five and 30% of respondents chose the neckline and shoulders-and-arms (upper and lower arms), respectively, as the attachment site for an LED-based communication. Respondents also considered the around-the-arm interface format as the most recognizable in terms of usability.

(2) Content Survey for Nonverbal Communication for People with Hearing Impairments: the questionnaire was carried out by categorizing the methods of LED-based visual communication and the preferred sensory parts of people with hearing impairments. The respondents were 30 members of the Korea Association of the Deaf in their twenties, thirties, or forties. All respondents expressed a need for smart fashion and had used a communication device or auxiliary equipment. Their scores were based on a 5-point Likert scale and in-depth interviews. The needs analysis revealed that smart fashion helps to resolve the communication disorders between people with and without hearing impairments. It also assists the hearing impaired individuals with their nonverbal communication through mutual feedback and allows them to partially communicate with individuals lacking knowledge of sign language. Finally, smart fashion promises to expand human functions and converts the information needed by people with hearing impairments into visual signals. These people communicate by cellular phone (46.6%), hearing aid

(26.6%), or both (26.8%). More than 80% of people with hearing impairments reported difficulty with communication exchanges. Respondents also desired to receive communications such as tactile (73.3%) and visual (26.7%) sensation through an intuitive interface. Visually perceptible wearable interface format, such as an LED, was rated satisfactory and average by 73.3% and 26.7% of respondents, respectively. These findings highlight the need for interactive smart fashion with an inbuilt visual communication feature, enabling intuitive interactions for people with hearing impairments.

(3) Survey on Detachable Modules and Wearable Interface Designs: the subjects (32 men and women aged 20–28 years participated in a survey and they had an interest and experiences with smart fashion.) reported their responses on a questionnaire based on a 5-point Likert scale, and in interviews. Eighty-one percent of the respondents reacted positively to wearable interface designs with human-friendly fasteners (buttons, sleeve bands, zipper sliders, buckles, stoppers, and Velcro). The favored fasteners were buttons (38.5% of respondents), strapped cuffs (30.8%), and zipper sliders (28%). In addition, 83% of respondents preferred to attach and detach their favorite functions and designs according to time, place, and occasion (TPO). Reasons for this preference included detergency, ease of management, usability, economy, compatibility, and sociality. These findings highlight the need for further research.

Considering these findings, our research team set a direction of promoting a LED-based smart fashion market by developing a user-centric content with VLC that fuses engineering and fashion design. The resulting design will satisfy the formativeness, wearability, purposefulness, economy, usability, satisfaction, and safety demands of the smart fashion market.

4. Method: Research through Explorative Design

4.1. LED as Design Material. LED, as a small device, can freely express the formative elements of line, surface, and space designs. They also create spatiotemporal patterns through light. Consistent with recent trends in emotion centric consumption, fashion design has increasingly focused on images and aesthetic sensitivity. With visualizing technologies of various colors, LED light-based wearable communication has the potential of creating a new market with original and creative high value-added fashion products that satisfy the fashion trends toward emotions and the smart fashion era. Recently, multidisciplinary researches have promoted these goals by exploiting the LED as design material. To highlight the use of LEDs as future design materials, this section introduces a typical case study of LED.

To improve the wearability of LEDs, researchers have applied textile-based methods or non-textile-based methods. First, the textile-based LED, based on a research on the conductive textile, has been studied as one axis of the electronic components, such as transistors and sensors [8]. Among the textile-based methods, the polymer light emitting electrochemical cell (PLEC) method achieves flexible, lightweight LED-based materials that can be woven into textiles like conventional clothes and which provide the same brightness from any direction [9]. Furthermore, PLEC materials can be manufactured by a high-speed, low-cost, roll-to-roll process that applies the dip-coating techniques widely used in fiber, thread, and fabric dyeing. Figure 1 illustrates a color-adjustable textile fabricated by the PLEC process [9].

Rather than illuminating the textile itself, non-textile-based methods aim to improve the physical characteristics of the LEDs incorporated into wearable devices. Colloidal quantum dot LEDs (QLEDs) are non-textile-based devices with unique optoelectronic properties such as color tunability, narrow emission spectra, high quantum yield, and photo/air stability. Additional advantages include printability on various substrates, ultrathin active layers, and high luminescence at low operating voltages [10]. Recently, ultrathin and wearable RGB QLEDs have been fabricated by a high-resolution intaglio transfer printing technique. Such QLEDs can be laminated onto various soft and curvilinear surfaces without diminishing the high EL efficiency. High-definition, full-color deformable QLEDs are expected to be realized in the near future [10]. Figure 2 presents electronic tattoos based on ultrathin wearable RGB QLEDs constructed by the high-resolution intaglio transfer printing technique [10].

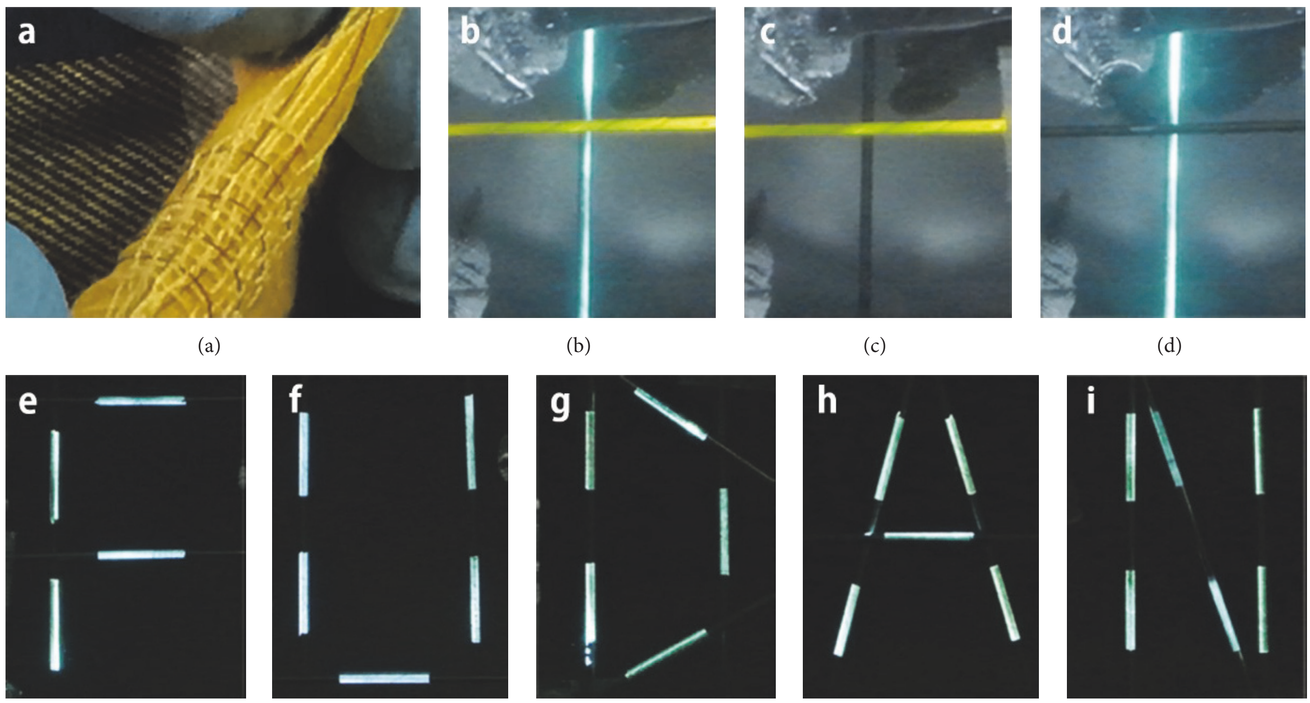
We expect that previous research will enable free design variations of wearable devices and also will provide more solutions to the designer of wearable devices by promoting the physical properties of LEDs in a wearable-friendly way.

4.2. Conventional Wearable Interactions Based on Led Light. With the growth of the wearable device market, now, it is not difficult to experience LED-based wearable interaction in the vicinity. This section analyzes existing LED-based interactive wearable devices, discusses their technical issues and the problems of conventional wearable interactions, and proposes new directions.

In the following representative cases, the functionality and decorativeness of LED light-based wearable technology are demonstrated in entertainment, communication, and safety functions.

Figure 3 presents Lumalive fabric with an entertainment function, which is used in the Lumalive textile garments of Philips [11]. This fabric creates dynamic advertising, graphics, and constantly changing color expressions through a luminous and flexible LED array inserted in the textile.

Figure 4 presents an interactive sound shirt with a communication function for people with hearing impairments [12]. By wearing this shirt, users can "listen" to an orchestra by feeling the vibrations of the instruments, which activate different parts of the shirt. An orchestral concert for people with hearing impairments was jointly organized and held by an orchestra team "Junge Symphoniker Hamburg" for people with hearing impairments and a company "CuteCircuit" which specializes in wearable technologies. The "Sound



(a) (b) (c) (d)

(e) (f) (g) (h) (i)

Figure 1: Integrated PLEC fibers and textiles: (a) textile subjected to bending and twisting, (b)–(d) two fiber-shaped PLECs selectively illuminated in different colors (biased at 10 Volts), and (e)–(i) weaving of fiber-shaped PLECs into a "FUDAN" pattern (biased at 9 Volts).

(a) (b) (c)

Figure 2: Electronic tattoo demonstrations based on ultrathin wearable QLEDs: (a) optical image of ultrathin green QLEDs laminated on crumpled Al foil and (b, c) photographs of the electronic tattoo (blue QLEDs) laminated on human skin (b). The wearable QLEDs maintain their optoelectronic performances even under skin deformations (c).

Figure 3: Lumalive textile garments with display functionality.

Shirt" software includes sensors that detect the important sounds of the bass, cello, and percussion instruments and translate them into vibrations, enabling users to experience the orchestral performance.

Figure 5 presents a garment with a safety protection function [13]. LED-based turn signals are installed in the front and back of the garment, allowing the wearer to view approaching people from all directions and thereby avoid rear accidents.

Inspired by the preceding examples, our interdisciplinary research team analyzed the content and applicability of LED light-based wearable interactions. From a technological

Figure 4: A Sound Shirt for hearing impaired individuals.

Figure 5: LUMENUS smart cloth with a safety functionality.

viewpoint, conventional LED-based wearable interactions can be divided into three types (see Figure 6). The first is a simple lighting for aesthetic effects, and the second is a light emission by responding sensors embedded in the wearable device. Finally, the third is the light emission indicating the operating status of a separate device such as a smartphone. As shown in Figure 6, the conventional LEDs play a comparatively passive role that depends on the types or applications of the prescribed wearable devices.

Along with the Lumalive textile garments in Figure 3, which possess an infotainment functionality, the typical example of type 1 interaction in Figure 6 is CuteCircuit's Galaxy Dress, which is pictured in Figure 7 [14]. Galaxy Dress is composed of 24,000 full-color pixels and a LED of $2 \times 2\,[\mathrm{mm}^2]$ size is flat like paper. Also, the Galaxy Dress, as an integration of the electronic device technology, does not overheat and consumes very little electricity. The heaviest part of Galaxy Dress is not the technology, but the 40-layer pleated silk organza crinoline that widens the skirt [14]. In recognition of the merits of fusing technology and fashion, the Galaxy Dress is the centerpiece of the "Fast Forward: Inventing the Future" exhibition at the Museum of Science and Industry in Chicago [14]. However, the conceptual design is limited, as it does not consider the users' situations or purposes when wearable devices are gradually evolving into life-friendly products.

Next, a representative example of type 2 interaction shown in Figure 6 is the "Sound Shirt," shown in Figure 4, demonstrating the visual communication function. The luminescence pattern and color of the LED dynamically respond to the loudness sensor. However, the application range and usability of this interaction are limited by sensor type and the surrounding environment. Nevertheless, this sensor-based interaction caters to the situations and purposes of hearing impaired persons and hence expands human functionality.

The third interaction type in Figure 6 visually informs the status of an external device such as a smartphone. A representative example is the smart ring of RINGLY, which indirectly receives notifications of five smartphone applications selected by the user (see Figure 8). The user-selected applications are distinguished by five emission colors of the LED attached to the accessory and four vibration patterns [15]. Xiaomi's smart band Mi Band also reports the status of the user's smartphone and checks the user's heart rate, distance traveled (number of steps), and sleeping patterns. To remove the functional ambiguity of the three LED indicators embedded in the initial version [16], Xiaomi recently developed Mi Band 2, which replaces the LED indicators with small organic LED displays [17].

Considering the three kinds of generic wearable interactions, present LEDs are potentially useful in smart fashion design despite their limited applicability in smart materials. Given that most wearable devices include a sensor and a battery, LED light can visually and intuitively indicate the operating state of a device, which is a very attractive feature. Nevertheless, as LED lacks many of the functional factors demanded for smart fashion materials, it is generally avoided in costume design. Specifically, LEDs are limited to visual effects (light emission patterns and colors), which restricts their applicability in wearable device of everyday life. Therefore, to utilize LEDs in the smart fashion market, which is gradually becoming specialized and systematized, we require aesthetically pleasing, functional wearable interactions that adapt to the situations and purposes of users.

5. Technical Implementation: Color-Independent Visual-MIMO System

To incorporate visible-light communication in wearable devices and smart fashion, our interdisciplinary research team applied the color-space based generalized color modulation (GCM) technique proposed by ourselves [18]. The research adopted the color-independent visual-MIMO (Multiple-Input Multiple-Output) system. Here, the modifier *"color-independent"* indicates the independence of the variations in the light color and light intensity and *visual-MIMO* means the visible light communication (VLC) between the light emitting array (LEA) and the camera.

5.1. Visible Light Communication (VLC). Generally, VLC refers to the technology for sending information by blinking the LED at a speed that cannot be perceived by human eyes. Here, the LED is used for transmitting the information, while a photo detector (PD) or a camera image sensor can be utilized as the receiver (depending on the application). In

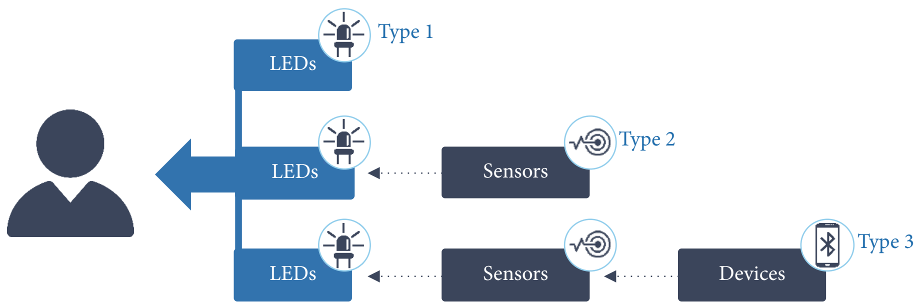


Figure 6: Three types of conventional wearable interactions based on LED light.

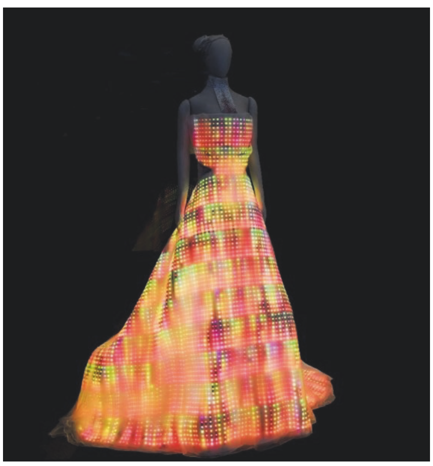


Figure 7: Galaxy Dress.

Figure 8: Smart ring of RINGLY.

the simplest case, digital data is sent through the LED by assigning the "on" and "off" of the LED light to the digital bits 1 and 0, respectively. The receiver decides the 1 or 0 status of the signal by detecting the changes in light intensity from the sensor. Recently, many studies about a camera image sensor as the transmission receiver have been conducted because most electronic devices (including smartphones) already contain a high-performance camera [2].

The low cost, energy efficiency, and environmental friendliness of LED elements and their extensive use of the existing infrastructure are advantageous for applying VLC in LED-based fashion. By adding a communication module and an appropriate smartphone application that controls the LED built-in smart fashion, any designer can incorporate LEDs into new interactions that are easily experienced by users. As in usual short-range wireless communication, the user can actively select and control the information to be delivered. Figure 9 demonstrates how VLC enables new wearable interactions in LED-based smart fashion. While maintaining its conventional functions, the LED can communicate with external devices through the VLC. The potential for new interactions will ultimately increase the value of LED-based design materials. Three types of VLC communication are discussed here.

Type 1: LEDs are attached to cloths and send some fixed information to Device 1 to Device N.

Type 2: LEDs can be attached to the locket. Sensors collect data and send the data to the device via LEDs.

Type 3: Almost similar to type 2 but here sensors receive data from another device via Bluetooth and LEDs are attached to the wearable device like watch.

In case of every type, multidevice interaction is possible, that is, one of the main advantages of the VLC communication.

5.2. Generalized Color Modulation (GCM). As a practical medium for transmitting data by VLC, the LED light must be carefully considered at the fashion design side because of its visible attributes. Most of the existing VLC systems have been developed for white lighting, which is unsuitable for fashionable clothing. The RGB LEDs in typical wearable devices (or smart fashions) are controlled by two parameters: color and intensity (brightness). In addition, as both parameters largely depend on the design requirements, the communication must perform under varying light color and brightness of the LEDs. This section introduces a modulation method that is optimized for combining the VLC technology with fashion design.

The first color-space-based modulation scheme, termed color shift keying (CSK), was proposed by the IEEE 802.15.7 task group [19, 20]. However, CSK is not suitable for communications when target color varies with time because

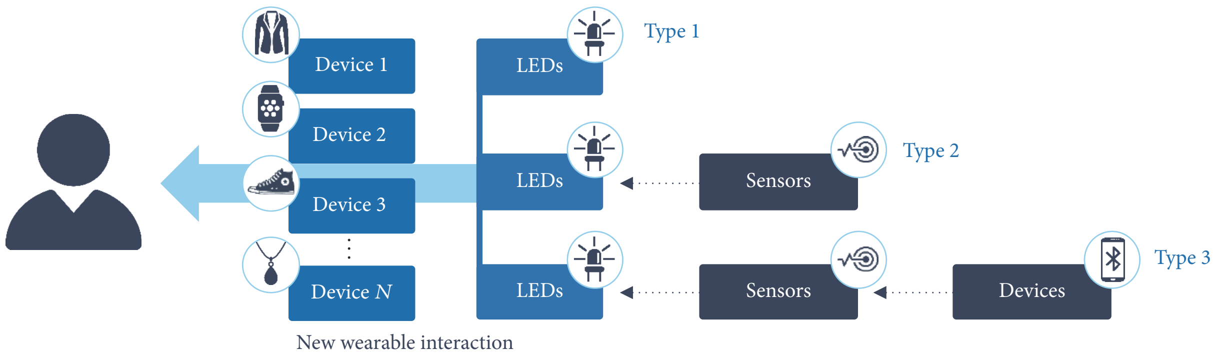


FIGURE 9: Block diagram of new wearable interactions through VLC.

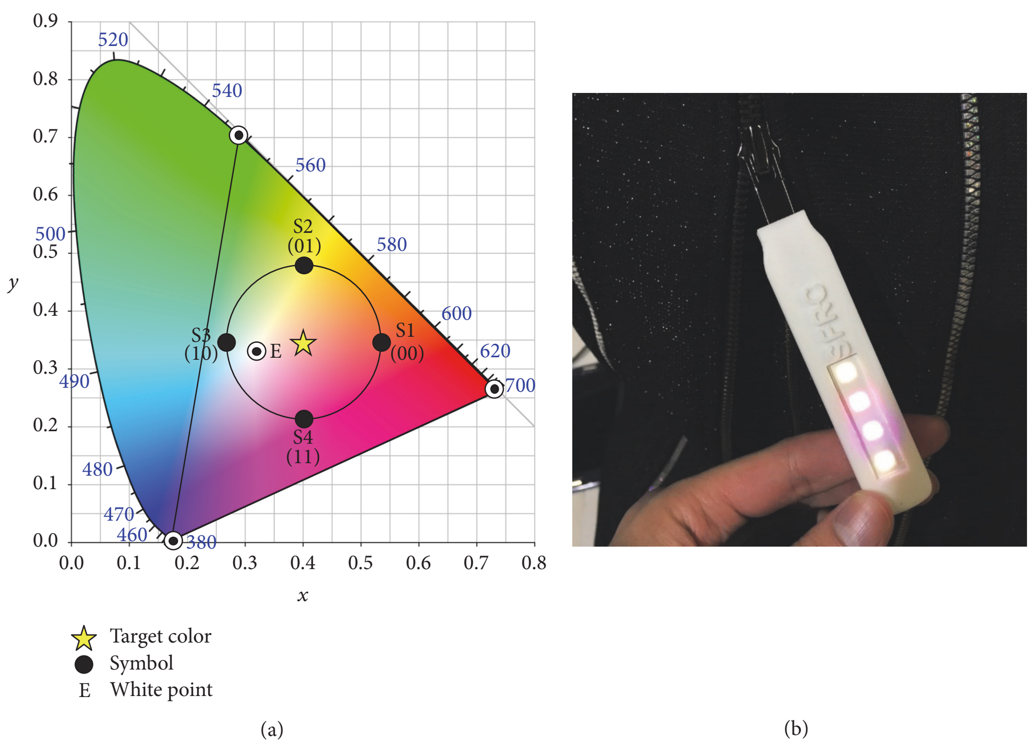


FIGURE 10: Example of GCM constellation and a prototype of color-independent VLC system: (a) example of GCM constellation and (b) prototype of color-independent VLC system.

it does not involve a systematic manner of coping with changing target color conditions. Here, the *target color* means the desired color of the LED lighting. In order to overcome this limitation, another color-space-based modulation scheme, termed as generalized color modulation (GCM), was proposed for color-independent VLC systems [18, 21]. It should be noted that the most distinctive feature and advantage of GCM over the other modulation schemes is color independency. GCM is able to generate any color within a gamut by combining some of the wavelengths or colors. Therefore, through GCM, we may achieve a VLC scheme that can maintain the original color and brightness while performing seamless communication. Figure 10 shows the example of color-space-based constellation and a prototype of the color-independent VLC transceiver. GCM constructs a constellation diagram in a light color space to represent data symbols. Each constellation point in the color space represents a corresponding color. Symbol color indicates the illuminating color of the LED depending on the input data, and the *target color* means a color perceived by the human eye when the symbol color changes rapidly at random [22]. Our proposed GCM method selects the number of transmitting symbols and the corresponding colors of the symbols in CIE1931 color space (see Figure 10(a)) and assigns digital bits to each color. Typically, when many symbols are illuminating randomly and rapidly through the LEDs, the human eye perceives the color of the LED as the average of multiple symbol colors.

The LED-color independency of GCM may be its most indispensable feature in fashion design. Designers of smart

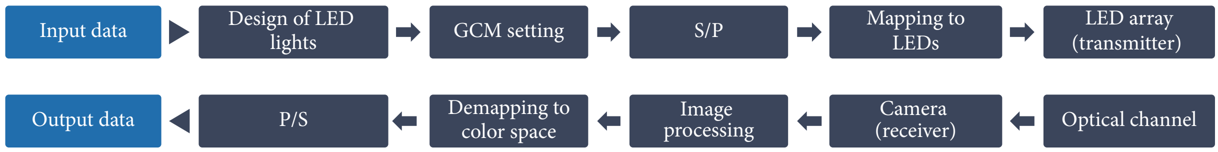


FIGURE 11: GCM-based visual-MIMO transceiving procedure with design of LED lights.

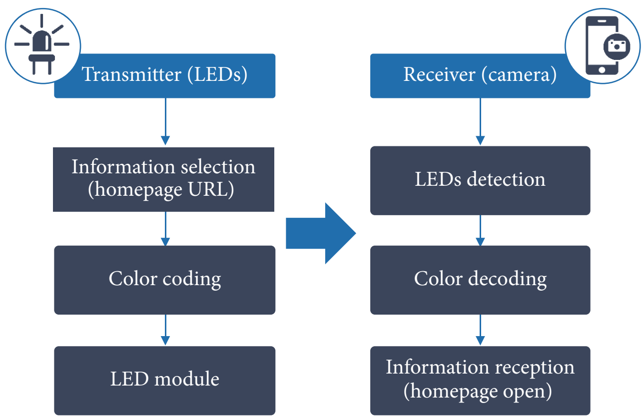


FIGURE 12: Block diagram of the transmitter (LEDs) and receiver (camera) in the "website-link" prototype.

wearable fashion must determine the color and brightness of the LEDs embedded in their products. The GCM method enables the engineer to maintain the color and brightness selected by the designer while performing seamless communication. Figure 11 shows a block diagram of the GCM-based visual-MIMO transceiving procedure, including the design of LED lights [23].

6. System Description: Transmitter (LEDs) and Receiver (Camera)

In the visual-MIMO system, the multiple transmitting elements of a light emitting array (LEA) are used as transmitters to communicate to the pixels of the camera (image sensor), which act as multiple receiving elements. This section explains how the transmitter and receiver of the color-independent visual-MIMO system interact through the "website links" prototype developed by our interdisciplinary research team. Figure 12 shows the overall operation of the "website link" prototype based on color-independent visual-MIMO.

The operation of each block in Figure 12 is outlined in the following.

6.1. Transmitter

(1) Information selection: first, the user selects the data to transmit over the Bluetooth platform of a smartphone. In the prototype, the color independence of the visual-MIMO system is demonstrated on the relatively simple URL address of an internet homepage. In actual use, the data type can be altered to suit the content of smart fashion.

(2) Color coding: the selected data (in this case, the URL address) are converted into color information by the GCM method, which digitizes the data to fit the communication protocol of the color-independent visual-MIMO system.

(3) LED module: the converted color information is sequentially mapped to multiple LEDs for fast LED emission.

6.2. Receiver

(1) LED array detection: referring to the image captured by the camera of a smartphone application, the LED array is detected by an image processing algorithm [24].

(2) Color decoding: each LED is located by analyzing the size and geometry of the LED array in the detected image. The symbol information is then obtained by determining and analyzing the color of each LED.

(3) Information reception: the data are recovered by converting the color (or symbol) information into digital bits through our GCM method. Finally, the smartphone application opens the homepage using the recovered data.

7. Design Strategies and Results

In the design industry of the 21st century, LEDs, backed by technological advancements, can realize multiple-sensory emotions that express rich human emotions. The expressive effects are functionality, aesthetics, interactions, and amusement.

More specifically, the various colors and fluid graphics patterns of LED work as aesthetic elements. Along with the unique functionality of light, these elements create brand images and attract consumers to the design industry. The long life and environmentally friendly nature of LEDs enable efficient, low-cost designs. Combined with digital technologies, the new media features of LEDs can entertain users with designs involving visual and emotional interactions.

Our research team fused engineering and fashion design to actively capture the emotions of consumers in our design products. To achieve a smart fashion prototype based on VLC, our team developed modular strapped cuffs and zipper sliders with the physical properties of clothing, which can be detached as desired by users. The technological aspects of the design manifest in the changing functionality of

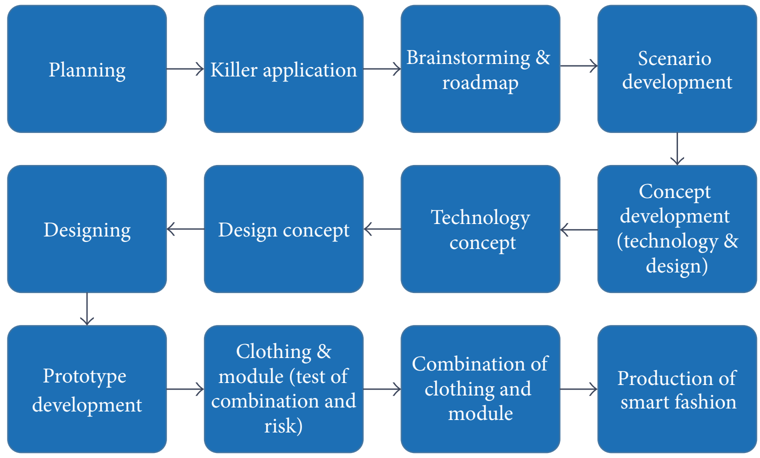


FIGURE 13: A process model of VLC-based smart fashion design.

the visual-MIMO communication (URL information in our scenario), which is implemented on the Bluetooth platform. In this design, users can adopt their own styles and individualities through the detachable modular approach.

7.1. Iterative Collaborative Design Process. The process model of the VLC-based smart fashion design fuses the processes with the desired characteristics developed in other fields. In developing the process model, we analyzed the methodologies of digital content, product design, and interaction design and incorporated them into the fashion process.

In the following we summarize the design process model by which we developed our stepwise strategy for the VLC-based smart fashion prototypes (see Figure 13):

(1) In the Planning and Killer Application Development stage, the content is tailored to users by exploiting the VLC and the correlations among men, clothes, and technology.

(2) The Brainstorming and Roadmap stage analyzes the design needs of the user and identifies the specialized VLC factors through the technology. Finally, it designs a killer application.

(3) The Scenario Development stage determines the scope of the VLC-based scenarios and VLC applied services. It writes a composite story by predicting the actual situations, including the circumstances and goals of users, and facilitates solid judgments rather than a two-dimensional, fragmentary understanding of problems.

(4) The Concept Development (technology and design) stage identifies the hardware, software, and formative elements of the design. The design concept is based on *who, when, what, how, and why*, context and content, and user interface and user experience. During this critical stage, the elements stemmed from the problems of technology and design-centric thinking are improved by a practical and specific implementation plan, which is applied in actual research. This stage must develop the user-centric content and investigate the fusion of engineering and design to meet the demands of users (namely, formativeness, wearability, purposefulness, economy, usability, satisfaction, and safety).

(5) The Designing stage applies and materializes the formative design elements. This stage involves styling, sketch design, the design of choices for sample production, drawing, modeling, and fitting. In the present design, the strapped cuffs and zipper sliders were rendered detachable from the VLC system if desired by the user. Users can also reorganize various platforms containing the clothing components of the smart fashion module. The outcome was a playful design by which users can enjoy the technology and its operation while satisfying their emotional needs.

(6) In the Prototype Development stage, our team developed a prototype of the trapped cuffs and zipper slider types with inbuilt information (URL information in the current scenario) conveyed through a Bluetooth platform. The modules were combined with clothing at this stage, and the prototype was demonstrated.

7.2. Multipurpose Smart Fashion by User Interfaces. If clothes-module combination has superior functionality but is fixed and nondetachable, its smart fashion will be of limited utility and will fail to provide a user-centric design. To resolve this issue, the components of our modular system can be detached as desired by users and are compatible with the details (strapped cuffs and zipper sliders) and fastening systems of conventional clothes. The modular system vastly improves the multipurposefulness, economy, usability, and detergency of the earlier smart fashion lacked. The approach began with the modularization of simple form to expand the diversity without requiring software and hardware changes. Individual user experience-based designs can be implemented by building diverse platforms that are modularized for each user. By simulating the fastening systems of clothes (such as snaps, zippers, Velcro, and clips), we overcome the reluctance of users to wear computerized technologies. These fastenings are

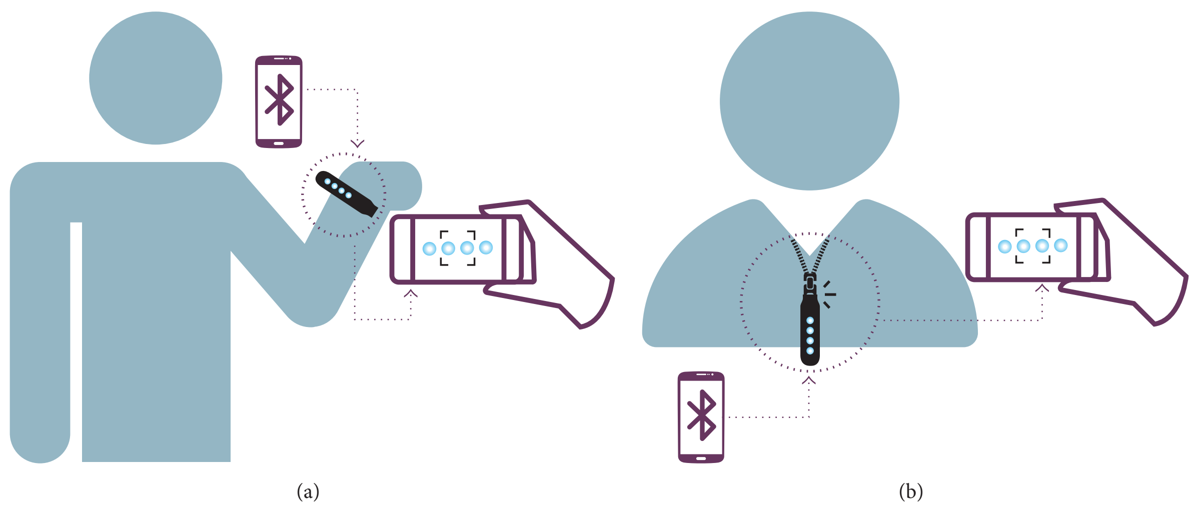


Figure 14: Communication between the transmitter (LEDs) and receiver (camera): (a) strapped cuffs type and (b) zipper slider type.

also familiar to users and are both functional and decorative. The developed fastening system is intuitively operated and adaptable to users' individual tastes.

The strapped cuffs and zipper sliders, proposed in our study, represent a multipurpose, adaptable smart fashion. Through the Bluetooth platform, users can alter the functions and designs of the smart fashion and continuously communicate with other users. The detachable modular system incorporates the functional module into clothing components that can be separated by fasteners (see Figure 14).

7.3. Interactive Smart Fashion for VLC. In the proposed scenario, two strapped cuffs and zipper slider types were applied to an interactive smart fashion, which nonverbally communicates information through VLC. This communication mode visually conveys the users' individuality.

Interaction (i) Scenario

(1) A user takes a walk at night.

(2) The walker meets an acquaintance by chance.

(3) The acquaintance requests the walker's blog address.

(4) With the walker's permission, the acquaintance (using the camera of a smartphone) photographs the walker's strapped cuffs (or zipper slider) embedding the visual-MIMO system.

(5) The blog address is automatically sent to the smartphone.

Interaction (ii) Scenario

(1) A user shops for clothes at the department store.

(2) The shopper desires to know the size, material, color, and other details of a clothing item.

(3) The shopper opens his 3D body avatar using the smartphone app.

(4) The shopper photographs the tag shaped visual-MIMO with his smartphone camera.

(5) The visual-MIMO system simulates the clothing item. The shopper receives the feedback without wearing the item.

(i) Strapped Cuffs Type. The cuffs band-type smart fashion module can be attached and detached through the Bluetooth platform developed by the research team. This fashionably smart module serves multiple purposes and functionalities by attaching and detaching the VLC-based strapped cuffs with a snap fastener, which is compatible with other clothes, or by attaching it to a zipper slider.

(ii) Zipper Slider Type. This module inserts a zipper slider with a clip fastener and can be detached according to users' tastes. The functionality and LED light source of this prototype are visually decorative, and the module alters the details of basic clothing items.

The research combined the elements of a smart fashion interface with shaped fastening systems that can be attached to clothes, alter the functions of clothes, and allow adjustment to different clothes (see Figure 15).

Design guidelines were incorporated into the technology and design concept, and the application planning of the elements was based on the analysis results of the user-needs survey. By this approach, the research team developed an interactive smart fashion prototype for the visual-MIMO communication. The prototype consisted of strapped cuffs and zipper slider type modules. To ensure a user-friendly product, the design guidelines were based on the four essential elements of a technology concept (usability, detachability, purposefulness, and economy) and of a design concept (usability, detachability, formativeness, and wearability).

Table 1 categorizes the technology and design concepts in the design guidelines of the interactive smart fashion for nonverbal communication through the visual-MIMO system.

Table 1: The design guidelines of interactive smart fashion for nonverbal communication through visual-MIMO communication.

Filed	Element	User needs	General plan
Technology concept	Usability	(i) Free of two hands, intuitional interface form needs. (ii) Communication: sight (LED), sense of touch (vibration sensor) (iii) Interactivity: using and care for simple, easy communication	(i) Transmitter (LEDs) and receiver (Camera) communication (Bluetooth Android Platform)
	Disadhesion	(i) Demand on disadhesion module in clothes (ii) Convenience through disadhesion (iii) Multipurpose and compatibility	(i) Disadhesion of module
	Purposefulness	(i) Taking into account situation and purpose to user	(i) Design disadhesion on user taste
	Economic feasibility	(i) Compatibility with other smart clothing, Take into account Economic feasibility	(i) Design of disadhesion a module
	Usability	(i) A decorative painting of technology (ii) Feeling in use of not computer instrument	(i) A source of light LED decorative painting of technology
	Disadhesion	(i) Fashionable needs to disadhesion and compatibility of module	(i) Disadhesion realization through fastener (ii) Strapped cuffs and zipper slider types
	Formativeness	(i) Everyday wearing positive, feeling in use of not computer instrument	(i) Details change on basic item
	Wearability	(i) Structural design of check body transformation	(i) Body move a little design on arm

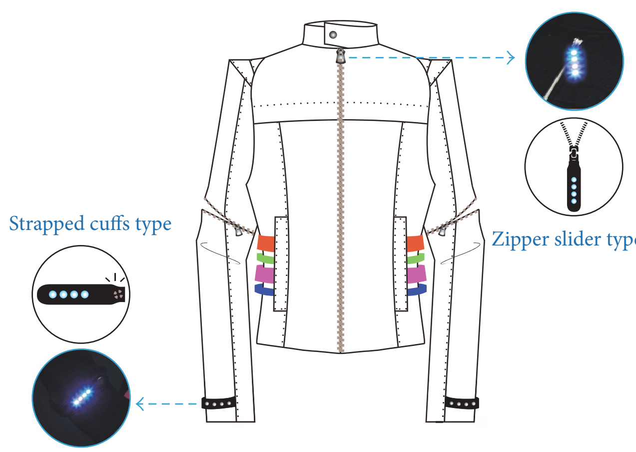


Figure 15: Dis-adhesion of smart module by a fastener: (left) strapped cuffs type and (right) zipper slider type.

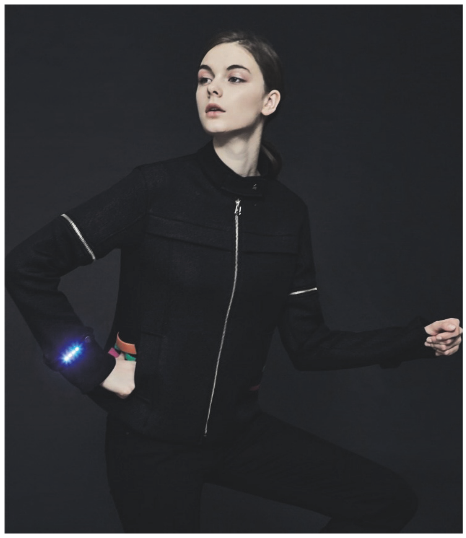
Figure 16 presents the strapped cuffs and zipper slider prototypes of the interactive smart fashion for visual-MIMO communication.

Reference [25] shows the implementation of our proposed idea. LED can be used as wearable device as well as pattern for communication. In Figure 17, to verify the performance of the prototype, symbol error rate (SER) was analyzed for 100,000 random symbol data while varying the distance between the transmitter and the receiver; the distances used were 0.5, 1, 1.5, and 2 m, respectively. In the 4×4 LEA, there was no error for distances up to 1.5 m, but 12200 errors occurred at 2 m. For the 4×1 LEA, the number of errors was 700, 520, 2100, and 64400, respectively. In the case of 4×1 LEA, since the standard deviation (SD) value of the synchronization data increases, the difference from the SD value of the information data decreases, so the synchronization error occurs more frequently and the performance degrades [23, 25].

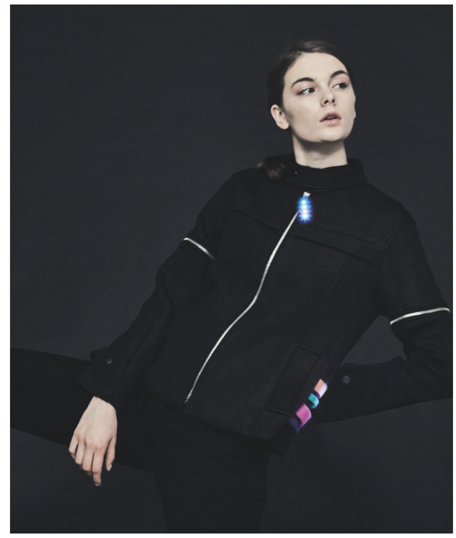
8. Conclusion

Interactive relationships in VLC-based smart fashion are formed between the individuals wearing LED-applied clothes and their observers, or among a group wearing LED-applied clothes. VLC-based smart fashion is organic, promoting interactive information flow through the wearable interactions and expanding the expressional forms of the wearable technology.

The proposed modular system can be detached as desired by the users. The system captures the details of real clothes (strapped cuffs and zipper sliders) and fastening systems by fusing technology with clothing design and is compatible with other clothes. The visual-MIMO system embedded in the clothing components is designed for versatile user tastes and allows users to operate from various platforms. The outcome was a playful design that satisfies the emotional needs of users through an enjoyable technology.

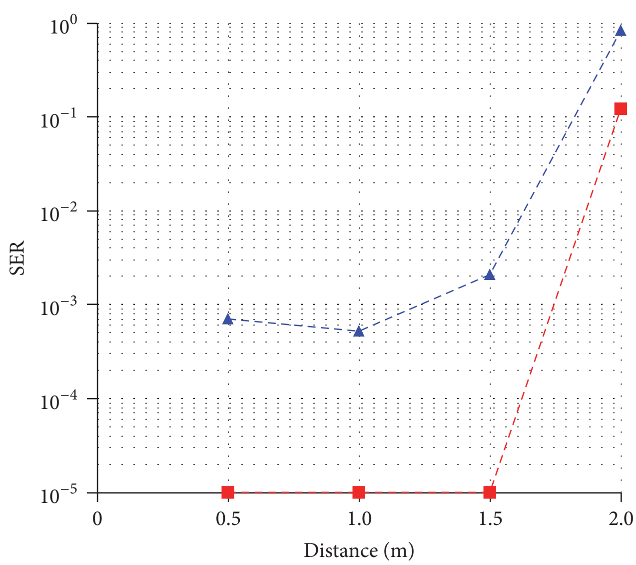


(a)



(b)

FIGURE 16: Prototypes of (left) strapped cuffs type and (right) zipper slider type.



LED: 4
LED: 16

FIGURE 17: SER performance versus distance.

The system preserves the aesthetics of old wearable devices and smart fashion by preventing the flickering of LED color and brightness. In addition, an image processing algorithm at the receiver end was optimized for wearable devices and smart fashion, and an interactive conversation system that delivers information nonverbally via LED light was developed.

The proposed color-independent visual-MIMO system communicates only through LEDs and camera image sensors. As no separate communication network is required, the system is potentially compatible with location-based service (LBS) and internet of things (IoT) services with the old LED infrastructure and smartphone cameras. Future technology is expected to further satisfy the goals of users through customized content development. The design characteristics of LED light (color and brightness) are visual and emotional elements. VLC-based technology will ultimately realize creative and original high value-added design products, giving the smart fashion industry a competitive edge in global markets.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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